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Governor

California Wind Energy Resource Modeling and Measurement

PIER FINAL PROJECT REPORT

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Abstract

This report presents the results of a project designed to improve the accuracy of wind resource estimates through advanced measurement, modeling, and mapping applications in several promising wind development areas of California. Five focus areas were identified: the Mojave Desert, San Gorgonio Pass, Tehachapi Pass/Antelope Valley, the Mayacamas Mountains, and Shasta Valley. For each area, high-resolution wind mapping simulations were run at twice the resolution of the existing statewide wind map, revealing modest adjustments to the intensity and structure of the local wind resource. A campaign of yearlong tall tower wind measurements and short-term sodar measurements was also implemented. These data supplied inputs to a boundary layer modeling research task intended to resolve key simulation problems. A modified statewide wind map was produced. Recommendations are given to expand new measurement and modeling initiatives to other areas of the state having development promise.

Keywords

Wind map, wind measurement, tall-tower, sodar, boundary layer modeling

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards funds to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

What follows is the final report for the *California Wind Energy Resource Modeling and Measurement Project*, Contract Number 500-03-006, conducted by AWS Truewind, LLC. The report is entitled *California Wind Energy Resource Modeling and Measurement*. This project contributes to the Renewable Energy program area.

For more information on the PIER Program, please visit the Commission's Web site at http://www.energy.ca.gov/pier/index.html or contract the Commission's Publications Unit at 916-654-5200.

Executive Summary

This project carried out several recommendations from a previous California Energy Commission (Commission) project entitled "New Wind Energy Resource Maps of California," Contract #500-01-009. That project developed the current statewide wind map and recommended research that could lead to improvements in the accuracy of the wind map. Three recommended areas of research were: (1) increase the resolution of the model runs in selected focus areas; (2) improve modeling capabilities of the atmospheric boundary layer; and (3) measure the winds at heights relevant to modern turbines, using tall towers and sodar systems, to provide research and validation data for the first two recommendations.

The objective of this project is to improve the accuracy of wind resource estimates in several promising wind development areas of California through advanced measurement, modeling, and mapping. The project consisted of five technical tasks:

- Selection of Focus Areas
- Focused High-Resolution Wind Mapping
- Measurement Program
- Boundary Layer Modeling Research
- Adjustments to the Statewide Wind Maps.

Following a screening process that considered over twenty candidate areas, five focus areas were identified: Mojave Desert, San Gorgonio Pass, Tehachapi Pass/Antelope Valley, the Mayacamas Mountains, and Shasta Valley. High-resolution wind mapping was conducted for the focus areas, with a final mesoscale resolution of 1 km and microscale resolution of 100 m, twice the resolution used to produce the current statewide wind map. The higher resolution model runs revealed that modest adjustments to the statewide wind map are in order within the focus areas because of the improved resolution of influential terrain features. The Measurement Program consisted of one-year of data collection at four tall towers at heights well above industry-standard meteorological masts, plus seven short-term sodar campaigns that measured wind profiles up to heights of 200 m. The boundary layer modeling research identified three key factors affecting simulation accuracy and took steps to better resolve these factors.

The principal benefits of the project to the State of California are:

- Enhanced wind map accuracy within promising wind energy development areas
- New measurement database at modern turbine heights covering 11 sites
- Improved boundary layer modeling and prediction capabilities.

These benefits will help improve the siting of future wind plants, yield more accurate energy production predictions for proposed projects, and enhance the skill of the scheduling and forecasting of next-hour and next-day wind plant outputs for

commissioned projects. It is recommended that other focus areas of the state be investigated through new measurement and modeling initiatives to improve the understanding of their wind regimes. This will broaden wind energy development opportunities in California.

Table of Contents

List of Figures

List of Tables

1.0 Introduction

1.1 Background and Overview

In a previous project for the California Energy Commission (Commission) entitled "New Wind Energy Resource Maps of California," Contract #500-01-009, TrueWind Solutions (now AWS Truewind) used its advanced MesoMap system to produce highly detailed maps and data files of the State of California's wind energy resources. The underlying purpose of the project was to encourage the development of wind energy in the State by helping companies and individuals identify promising wind project sites with a minimum of effort. The maps were validated using wind measurements from 266 locations throughout the State, including airports, ocean buoys, and towers instrumented specifically for wind resource assessment. This validation process determined that the mean wind speed estimates were accurate to within a standard error of about 0.4-0.6 m/s, or 6-8%, at a height of 50 m above ground.

Although the new maps and data files represent a major advance over the previous understanding of the State's wind resources, there was room for improvement. A standard error of 6-8% in mean speed implies an uncertainty margin, within 95% confidence, of roughly 20-30% in wind turbine output. In the final report of that project, several issues affecting the accuracy of the wind resource estimates were identified, and the following recommendations for further research were presented:

1) High-resolution modeling of select areas. Certain aspects of California's unusually complex wind regime, such as blocking by coastal mountains and channeling through narrow passes, could not be modeled very accurately at the 2 km grid scale of the MASS model simulations. As tests carried out by AWS Truewind have shown, higher resolution MASS runs could improve the accuracy of the wind resource estimates in promising development areas.

2) Analysis of boundary layer issues. The stability of the nighttime boundary layer has a major impact on the wind resource in certain parts of California, particularly the desert, where it may insulate the surface from high winds aloft. However, it poses a significant modeling challenge that could not be fully explored in the previous project. In-depth research on methods of simulating stable atmospheric conditions could substantially improve the accuracy of the wind maps in such areas.

3) Measuring the wind aloft. Most of the towers that provided data for the validation of the statewide wind map were less than 20 m tall, and lack of knowledge of the wind shear above that height consequently introduced a large uncertainty in the wind resource that would be experienced by modern wind turbines. New measurements using tall towers in promising areas are clearly needed. However, even the current standard 50 m towers do not reach the hub height of

modern wind turbines, which is typically 65-80 m, let alone the tops of their blades which may approach a height of 150 m above ground; and taller towers are expensive. Existing communication towers, however, can offer a relatively inexpensive platform from which to take direct wind measurements at relevant heights in the vicinity of 100 m above ground. New techniques such as sodar can measure the wind to heights of 200 m or more at a moderate cost. In addition to exploring the wind resource at a particular site, sodar could be useful in validating and refining models to simulate the boundary layer, with benefits in other areas being mapped.

4) Land cover data research. The impact of land cover data quality on the accuracy of the initial statewide map was unknown.

1.2 Project Objectives

The objectives of this project are:

1) Generate high-resolution wind resource maps targeting focus areas of complex terrain and meteorology believed to have promising wind development potential; and

2) Provide measured wind data at heights representative at heights above traditional meteorological masts (50 m).

With successful completion of this project, the State will possess one of the highest horizontal grid resolution maps at 200 m with regional refinements at the 100 m level. These refinements are expected to increase the overall accuracy of the maps within the focus areas by 50%. The State will have contributed to improving the accuracy and refinement of the state-of the-art for atmospheric modeling technology, thereby improving the quality of wind mapping and forecasting services available to industry. The project will provide the first publicly available wind measurements using tall towers and complementary sodar technology targeting the 50 m-200 m height interval, which is directly representative of today's large-scale wind turbines.

This project meets the PIER goal of improving the reliability and quality of California's electricity by more accurately defining wind resources in the State and identifying areas of untapped or underdeveloped wind potential. This project also helps to improve energy cost/value of California's electricity by providing better understanding of wind resources and helping to increase market penetration levels through coupling numerical modeling capabilities with meteorological mast monitoring. This project is expected to help increase market penetration by both small and large wind technologies.

1.3 Outline of Report Organization

The report is organized to provide an overview of the entire project. Section 2 summarizes the project approach, which consists of five technical tasks. Section 3 presents the key outcomes of the tasks. Finally, Section 4 discusses the project's conclusions and recommendations and addresses the project's commercialization potential and benefits to California.

During the course of this project, final reports were submitted for each of the major technical work tasks (Task 1 was administrative in nature):

- Final Focus Area Selection Report (Task 2)
- Final Map Draft Comparison Report (Task 3)
- Final Detailed Measurement Program Plan (Task 4)
- Measurement Program Final Report (Task 4)
- Final Boundary Layer Research and Findings Report (Task 5)
- Final Statewide Wind Maps & Modifications Report (Task 6)

With the exception of the Measurement Program Final Report, these reports are included in the appendix of this document and should be consulted to obtain more details about the individual tasks. The Measurement Program Final Report is available as a separate document.

2.0 Project Approach

This section summarizes the five main technical tasks (and associated subtasks) comprising the project: (1) Selection of Focus Areas, (2) Focused High Resolution Wind Mapping, (3) Measurement Program, (4) Boundary Layer Modeling Research, and (5) Adjustments to the Statewide Wind Maps.

2.1 Selection of Focus Areas

Selection criteria for the focus areas were defined as:

- The areas should offer significant promise for wind energy development after considering important siting factors;
- Two areas should be within the major, known wind resource areas of the state;
- The remaining three areas should be relatively unexplored and offer the potential for new, large-scale project development;
- The focus areas should represent a variety of terrain in order to adequately test the wind modeling process. One focus area should contain a mountain pass.
- The focus areas should also investigate regions of particular interest to the Commission. One of the areas should be in Northern California; another should be in the Mojave Desert.

It was also desired that tall towers (e.g., communication towers) exist within or near the focus areas so that the meteorological measurements activities of the Measurement Program can be co-located.

A cost-based site screening approach using a geographical information system (GIS) was developed to identify the most cost-effective sites able to support wind project sizes of at least 50 MW. Factors considered include:

- Wind resource as defined by the statewide wind map
- Elevation and air density
- Proximity to transmission
- Proximity to populated areas
- Exclusion of park lands, wilderness areas and conservation areas
- Exclusion of water bodies
- Exclusion of steeply sloped terrain (>15%), which is generally not negotiable by heavy trucks carrying large turbine equipment components.

This approach used capital and construction cost assumptions for wind plants and for roads and transmission lines (including substations), which accounted for distances from existing facilities. Wind plant capacity factors were calculated by matching wind map-derived resource statistics with a generic turbine power curve reflecting current megawatt-scale wind technologies.

From the site-screening results, 22 candidate areas were chose as potential focus areas to satisfy the project selection criteria.

A tall tower search scheme was then applied to the 22 candidate areas to determine those meeting the requirements of the meteorological measurement activities of the Measurement Program. This scheme utilized public datasets as well as information gathered from site visits and in-state contacts.

The results of the above steps were compiled and evaluated, leading to the selection of five final focus areas. The focus areas are named in Section 3.1 and are presented on a map in Figure 1. One focus area is in northern California, another is in the state's central region, and three areas are located in southern California.

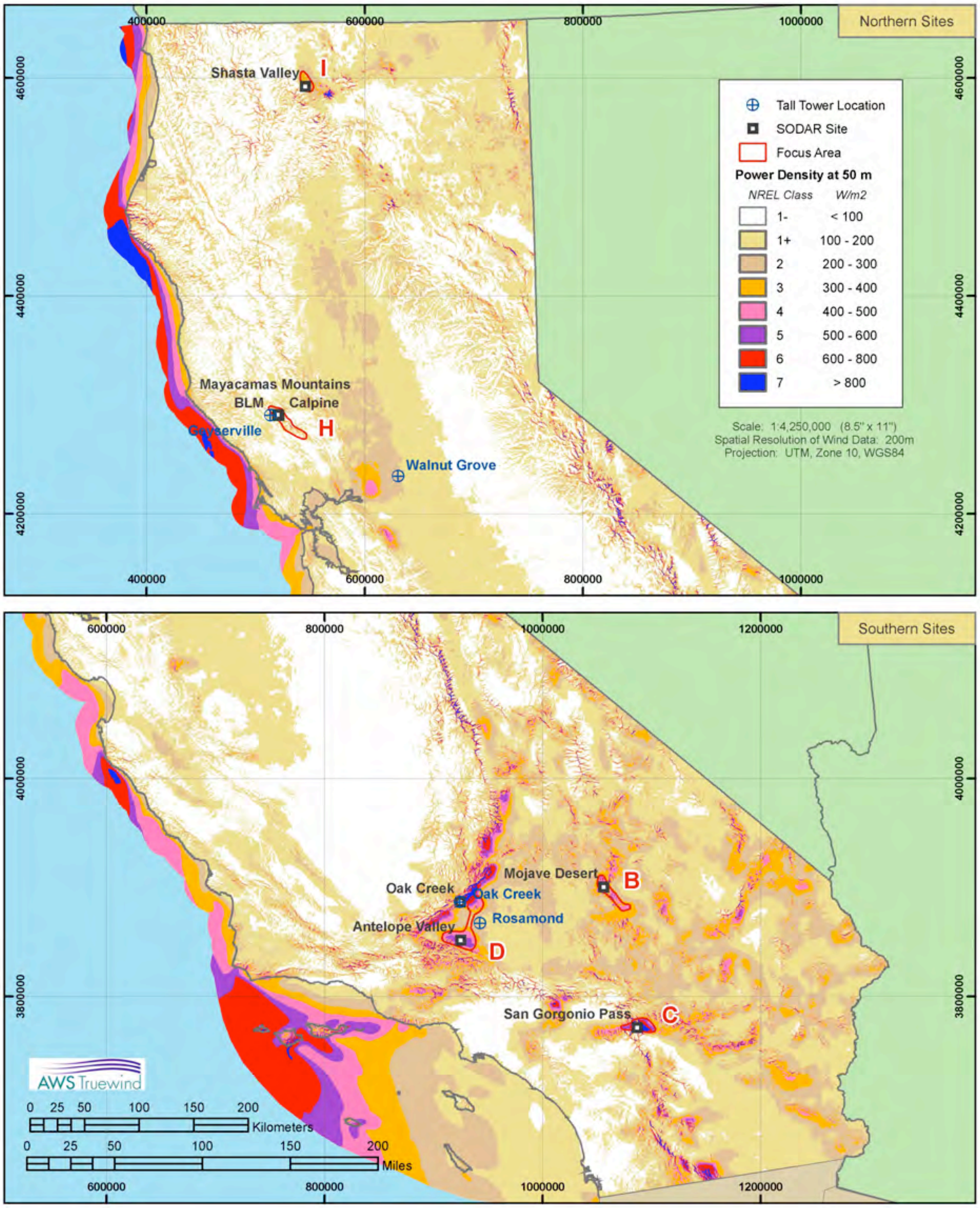

Figure 1: Overview of Focus Areas as well as Tall Tower and sodar locations Tall Tower and reference station locations

2.2 Focused Wind Mapping

The wind resources for the five focus areas were remapped using a mesoscale resolution of 1 km and a microscale resolution of 100 m. The maps were compared with the statewide wind maps, which were originally produced in steps of 2 km (mesoscale) and 200 m (microscale) resolution. Where available, the map results were compared with existing meteorological data. However, since this task occurred before completion of the Measurement Program task, data collected during the Measurement Program were compared to the high resolution maps as part of the final task (Section 2.5).

2.3 Measurement Program

A wind measurement program was conducted for the five focus areas. An existing tall tower was used to collect multi-level meteorological data for a full year within three of the five focus areas as well as one candidate focus area (an appropriate tall tower was not available for the fourth and fifth focus areas). Sodar measurements were taken by applying a short-term (up to 5 weeks) campaign strategy at one or two sites within each focus area. The overall measurement period began in April, 2004 and was completed in July, 2005.

A detailed measurement program plan was written to guide the tall tower and sodar campaigns. It specified:

- Site locations
- Measurement period
- Instrumentation preparation, calibration, installation and maintenance protocols
- Data processing and analysis protocols

A summary of this plan is presented as the following two subtasks.

2.3.1 Tall Tower Campaign

Tower leases were negotiated with tower owners and tower wind loading studies were performed as needed.

The two towers in central California (Transtower and Geyserville) and two in southern California (Oak Creek and Rosamond) were instrumented at three levels to collect wind speed and direction data. Primary and redundant anemometers and a wind vane were installed at three levels per tower. Pyranometer and temperature sensors were installed at the tower's lowest section. When not impeded by radio frequency interference, calibrated temperature sensors were also installed at the top of the tower to measure thermal stability across the height of the tower, thereby assisting the Boundary Layer Modeling Research task.

At three of the towers, sensors were mounted at a sufficient distance from the tower face to meet the International Energy Association's (IEA) specifications for the instrumentation of tall towers. The one tower not instrumented to IEA specifications (Transtower) had a face width greater than 12 ft. Instrumenting the fourth tower to IEA specifications was not feasible due to budgetary constraints. Tower riggers were contracted to install the equipment, with their work overseen by an AWS Truewind engineer. Equipment maintenance contracts were executed with an in-state firm.

Recorded meteorological data were transmitted via cellular or landline service to AWS Truewind and validated monthly. After a year of recording at each site, the data were analyzed and correlated with regional long-term reference measurement sites (e.g., National Weather Service stations), using the measure-correlate-predict method (MCP), to project the long-term wind speeds. The tower equipment was subsequently decommissioned.

2.3.2 Sodar Campaign

Sodar siting permission was acquired from the various landowners of each site (consisting of private individuals, businesses, municipalities, or federal agencies). Two sodar units were deployed simultaneously for the seven-site sodar campaign. The sodar units were transported to each site, set up, and tested by an AWS Truewind engineer. The units were operated at each site for two to five weeks. The units were calibrated before each siting. AWS Truewind or its subcontractors provided scheduled and unscheduled maintenance services. Data were reported via cellular internet connection or manual data retrieval. Data sets were validated and compared to concurrently measured data from the tall towers as well as from nearby reference stations.

2.4 Boundary Layer Modeling Research

The first step was to identify the typical modeling biases and problems. The next step was to identify those problems that were likely related to the boundary layer. The final step was to identify the meteorological cases that were representative of a given boundary layer related problem in order to perform model experiments in an attempt to identify the source of and solutions to the problems.

Two approaches were used to help identify modeling problems relevant to the boundary layer. One approach was an objective statistical analysis of the model output of many cases with observations from various sources to determine where the model was having problems simulating the boundary layer winds. The other approach was a subjective point comparison of model soundings with observed soundings for individual cases. The analysis involved comparing observed wind speed data from sodar, towers, rawinsonde and standard surface weather observations with the model output. There were three categories of modeling problems identified from the field measurements that were most likely related to boundary layer problems.

2.5 Adjustments to the Statewide Wind Maps

The results of the Focused High Resolution Wind Mapping task were reevaluated given the results of the Measurement Program and Boundary Layer Modeling Research tasks. Areas with significantly improved results, verified by measurement, were incorporated into the previous statewide wind map. A new state wind map and accompanying data files were produced and submitted.

3.0 Project Outcomes

3.1 Selection of Focus Areas

The five focus areas selected were:

- Mojave Desert (Focus Area B)
- San Gorgonio Pass (Focus Area C)
- Tehachapi Pass and Antelope Valley (Focus Area D)
- Mayacamas Mountains (Focus Area H)
- Shasta Valley (Focus Area I)

The San Gorgonio Pass as well as a portion of the Tehachapi/Antelope area are within well known, developed wind energy regions. They are viable locations for the repowering of current projects and construction of new projects. A variety of terrain types are encompassed within the focus areas, including passes, valleys, and mountain ridges. Shasta Valley is in northern California, and the Mojave Desert area is approximately 120 km east northeast of the Tehachapi Pass. All of the screening criteria developed for this task were fulfilled.

3.2 Focused Wind Mapping

Below is a summary of this task's outcome for each focus area. All task objectives were met.

3.2.1 Mojave Desert

The new maps indicate a >10% increase in mean speed in the middle of the area. This enhanced area is in the outflow from a gap between the Calico Mountains and Lane Mountain to the west. This suggests that, at a higher resolution, the model simulates more channeling through the gap. There is a similar but smaller increase in wind speed at the eastern edge of the area at an outflow zone. By contrast, the large area of channeled flow through the Mojave Valley was relatively unaffected by the higher mesoscale resolution, except that it was extended somewhat farther to the east. This indicates that the original mesoscale resolution was sufficient to resolve this pass, but not the other two, smaller passes.

3.2.2 San Gorgonio Pass

The new map shows an area of increased speed through the middle of the pass and particularly out the eastern end, and also extending southeast into the Coachella Valley. This was not surprising because of the ability of the mesoscale model to better resolve the pass and its outlet at the higher resolution. Once again, in the mountains, there was a more complex pattern of increases and decreases, with most ridgelines experiencing a moderate increase in the predicted wind speed. A comparison of the original (unadjusted) and new maps with validation data from 18 stations gathered in the first project showed a clear improvement in map accuracy. The adjustments applied to the raw map in the first project were quite similar to the changes resulting from the higher resolution.

3.2.3 Tehachapi Pass and Antelope Valley

As with the San Gorgonio Pass, there was a clear pattern of significant increase within and downwind of several passes, most importantly Tehachapi Pass, but also two others, the one to the south known as Cottonwood, and the other to the north, Lone Tree Canyon. The increased wind resource out of Tehachapi Pass extended well out onto the valley floor. Accompanying the increase in the wind resource in the passes, there was a decrease downwind of the higher parts of the Tehachapi Mountains. This was expected, given that, with higher resolution, the MASS model simulates greater blocking of the shallow flow by the mountains, and correspondingly greater flow through the passes. The new map was compared with validation data (25 stations) and an improvement was seen. The original (unadjusted) wind map had very little bias overall (about 0.1 m/s), but the standard deviation between the data and map was 1.15 m/s. With the high-resolution map, the bias remains small (-0.1 m/s), but the standard deviation is reduced to 0.87 m/s.

3.2.4 Mayacamas Mountains

The comparison of the new map to the original map presented a rather complicated picture. The average change in mean speed across the whole region was about -6%, i.e., a moderate decrease. This was probably mainly due to increased sheltering of the valleys in the high-resolution simulations. There were a few exceptions – broad valleys which, perhaps because of their orientation to the prevailing wind, were predicted to have a somewhat greater wind resource than in the original wind map. Within the mountains, the impacts of higher resolution were too complicated to be easily interpreted. Most of the variations in the speed ratio were on too small a scale to have anything to do with the mesoscale model. Rather, they reflected small differences in elevation at the microscale. The impact was particularly noticeable on sharp mountain peaks, where slight changes in elevation due to the change in resolution can result in substantial changes in the predicted wind speed. A close examination of the main ridgelines – which are the only areas in the region with a potentially attractive wind resource – reveals a slight decrease in the maximum predicted wind speed. This is to be expected since, at a higher resolution, the mesoscale model was able to simulate more mountain blocking. The impact, however, is quite modest – typically a few percent, or 0.1-0.3 m/s.

3.2.5 Shasta Valley

As with the Mayacamas Mountains, the comparison of the new map to the statewide map presented a complicated picture. Focusing on the Shasta Valley, it appears that higher resolution has enhanced the predicted outflow from the mountains, particularly on the west side of the valley.

3.3 Measurement Program

A total of four years of tall tower wind data plus six months of sodar data were collected at the four towers sites and seven sodar sites seen in Figure 1. All objectives of this task were fulfilled.

3.3.1 Tall Tower Campaign

Data recovery for the four tower sites was excellent, averaging 96.8%. Except for the Geyserville tower, the highest wind speeds were observed during the late spring and summer months. This was caused by the large continental/marine temperature and pressure gradients that develop during the spring and summer months when the strongest solar heating occurs. Increasing wind speeds between the late morning and mid- to late afternoon hours were observed at all sites. Rosamond was the most strongly affected by the sea breeze because the peak daily winds are observed at around 4 PM before they dropped sharply with the decrease in daytime heating. The other three sites experience nighttime wind speed maxima that were related to boundary layer stabilization and their respective elevations. The wind roses at Oak Creek, Transtower, and Rosamond were all driven by channeling. At Geyserville, the wind direction is more variable than at the other sites due to complex terrain.

The Oak Creek and Transtower sites were both equipped with high-accuracy temperature sensors at two levels to study the effects of stability on the boundary layer wind conditions. Both locations experienced stable conditions during the overnight hours and unstable conditions during the day.

Table 1 summarizes the long-term wind speed projections for the four sites.

Table 1: Tall Tower long-term wind speed projections

Monitoring Site	Monitoring Height (m)	Wind Speed Projection (m/s)	Mean Wind Shear	70 m Wind Speed Projection (m/s)	100 m Wind Speed Projection (m/s)
Oak Creek	88.4	8.13	0.240	7.67*	8.38
Rosamond	109.7	6.89	0.240	6.16*	6.74
Transtower	111.3	6.03	0.332	5.23*	5.82
Geyserville	60.1	5.90	0.087	5.98	6.17

*The 70 m wind speed projection was derived through shear extrapolation from the middle level anemometer because it was closer to 70 m than the top sensor.

3.3.2 Sodar Campaign

Sodar availability at the Antelope Valley and Oak Creek sites was 100% and 92% respectively. Comparison of Oak Creek sodar data with Oak Creek tower data resulted in a slope of 0.87 and an intercept of 1.05 m/s, with an R^2 of 0.80. The values are not expected to match due to the complex terrain and siting within an active wind farm, resulting in significant wake effects. The 80/50 m shear exponent at Antelope Valley for all periods and for periods with 50 m speeds ≥ 5 m/s were both 0.08. Oak Creek 80/50 shear for all periods and for periods with 50 m speeds ≥ 5 m/s were 0.23.

Overall sodar availability was 100% and 73% at the Mayacamas and Calpine sites, respectively.

The wind speeds at the Mayacamas and Calpine sodar sites were generally lower than those at the Geyserville tower site. Differences between the sodar and tower speeds were expected given the distance among the sites as well as the extreme terrain complexity. The steep terrain around both sodar sites leads to very low, sometimes even negative, shear. Overall the Mayacamas site had an 80/50 m shear of 0.23 and 0.17 for speeds ≥ 5 m/s. Calpine had an overall 80/50 shear of 0.24 and 0.08 for speeds ≥5 m/s.

At the Mojave site, the overall availability of the sodar was 60%. All of the data loss was due to a high-temperature shutdown of the power system, which was diagnosed and repaired. The campaign was prolonged to ensure collection of a representative dataset. The overall 80/50 m shear exponent for observations with 50 m speeds ≥ 5 m/s was 0.10, and 0.16 for all speeds.

At the San Gorgonio site, the overall availability of the sodar was 99%. The 50/80 m shear exponent was 0.11 for all 50m speeds, and 0.12 for 50 m speeds ≥ 5 m/s.

At the Shasta site, the overall availability of the sodar was 98%. The study period was characterized by weak winds punctuated by episodes of strong southeasterly winds. The 80/50 m shear exponent was a low 0.1 for cases where the 50 m wind speed was ≥ 5 m/s, and 0.1 for all speed cases as well.

3.4 Boundary Layer Research

Three categories of modeling problems were identified as most likely related to boundary layer problems:

- Atmospheric stability
- Terrain complexity
- Surface energy budget formulation.

All objectives of this task were fulfilled.

3.4.1 Atmospheric Stability

Problems related to atmospheric stability generally seem to be the result of the model not being able to resolve or properly handle the energy transfer within the boundary layer during periods when the boundary layer is stable. This problem is most noted during the late evening and early morning hours during periods of clear skies. The surface, rawinsonde, tower and sodar observations all indicate that during these stable periods, there is a tendency of the simulated winds to be higher than observed.

Experiments were run with different mesoscale mode resolutions, types of activated stability regimes, and boundary layer formulations. All three were shown to effect boundary layer problems. In particular, the z-less boundary layer formulation scheme showed particular promise for resolving such problems.

3.4.2 Terrain Complexity

Three different factors were tested to improve terrain complexity problems. First, non-hydrostatic model results were compared with hydrostatic results. Cases were discovered where a non-hydrostatic mesoscale model performed better, especially for extreme down slope conditions. But in most cases there was very little difference between the hydrostatic and non-hydrostatic wind speeds. These differences would not be significant when creating a long-term climatology of the wind speeds.

Tests with different models (MASS, OMEGA, and WRF) show little difference between MASS and WRF. OMEGA provided some improvements but underestimated wind speeds and produced unrealistic results. However, the OMEGA model also requires roughly five times more computing runtime as the MASS model and thus does not appear to be advantageous.

3.4.3 Surface Energy Budget Formulation

Four types of experiments were performed to improve surface energy budget formulation problems:

- Non-hydrostatic versus hydrostatic experiments
- Resolution experiments
- Sensitivity to mesoscale model used
- Sensitivity to input data surface and atmospheric data

Non-hydrostatic versus hydrostatic, resolution, and model type were not primary factors of surface energy budget problems. However, input data had a significant impact. In particular, the availability of both rawinsonde and surface data improve model performance. More significant improvements were noted with the use of:

- Updated soil moisture data, accounting for newly irrigated lands in the Coachella Valley
- More accurate sea surface temperature data, which also included larger inland water bodies (such as the Salton Sea).

3.5 Adjustments to the Statewide Wind Maps

Not enough data were available in the Mayacamas Mountains, Mojave, and Shasta Valley focus areas to determine if the higher resolution maps were a significant improvement over the statewide map. Therefore, no adjustments were made to the statewide maps in these areas.

In the San Gorgonio area, the changes resulting from the higher resolution simulations were similar to the manual adjustments that were made to the original maps during the validation. For this reason, no further adjustments were required in this area.

In Tehachapi Pass, the spatial pattern of changes due to higher resolution modeling was quite different from the manual adjustments. Moreover the combination of the manual adjustments and higher resolution produced a more accurate map than either alone. Therefore, the higher resolution Tehachapi map was incorporated into the adjusted statewide wind map. See Figure 2 and Figure 3.

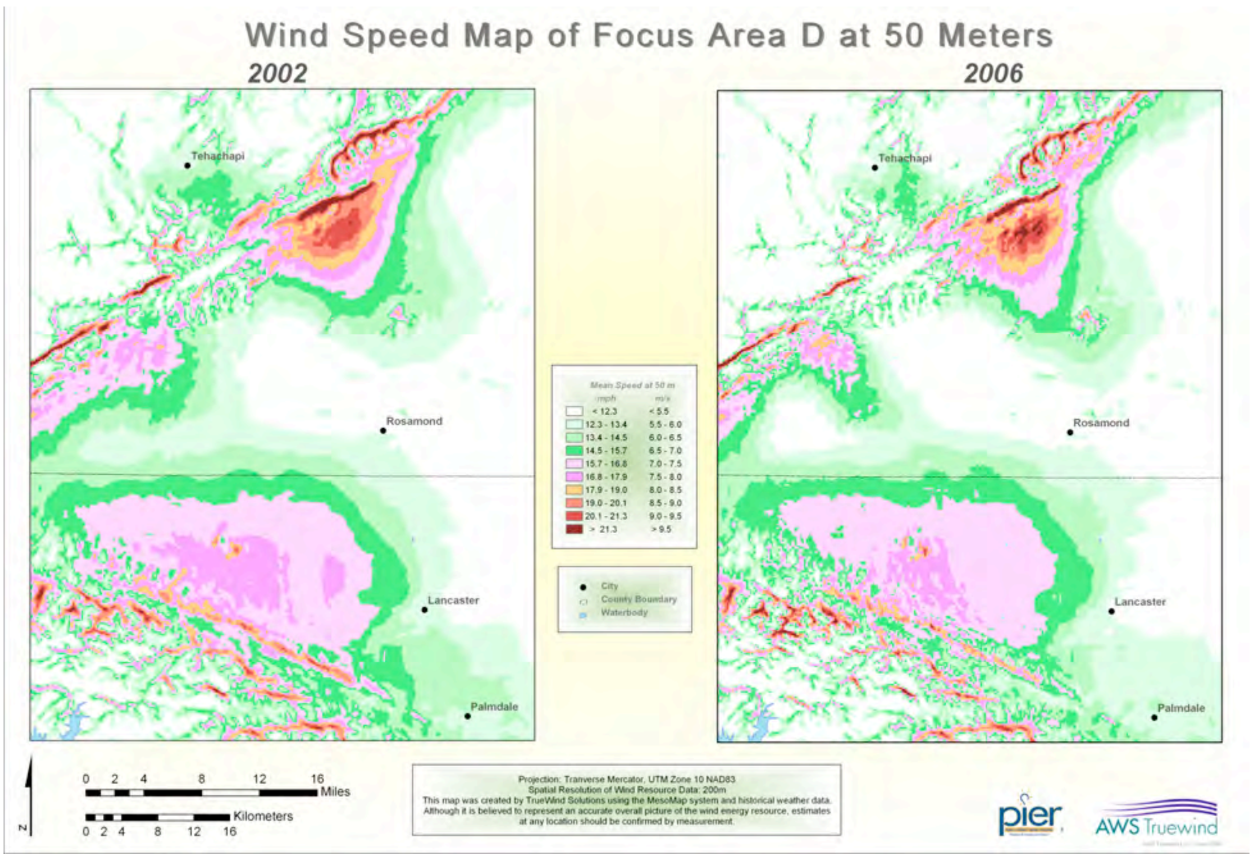

Figure 2: Comparison of 2002 and 2006 wind speed maps for Focus Area D

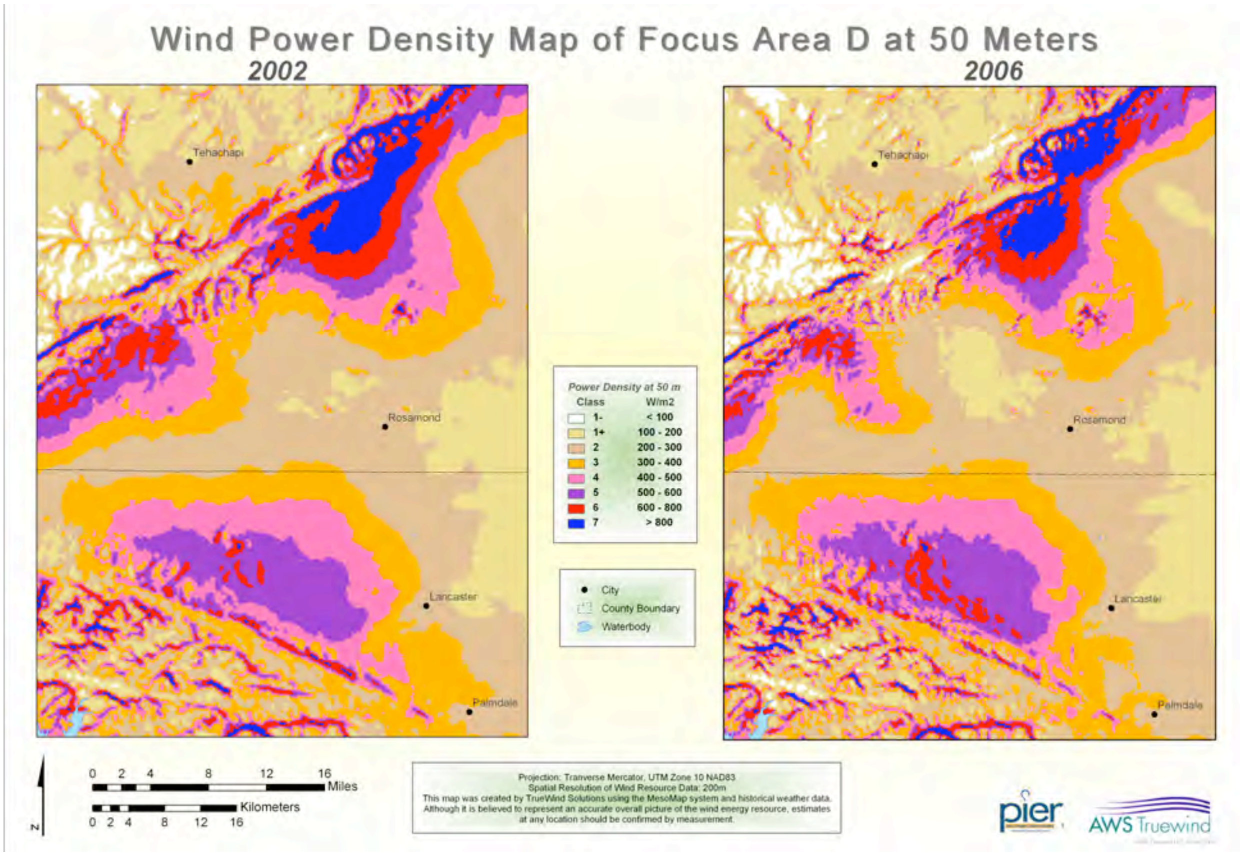

Figure 3: Comparison of 2002 and 2006 wind power density maps for Focus Area D

The Boundary Layer Modeling Research task determined that the accuracy of the mesoscale simulations could be improved by implementing a “z-less” boundary layer formulation as well as a new soil moisture database, which takes into account irrigation, and a new sea-surface temperature database. However, it would not be possible to apply a systematic correction to the statewide wind resource maps to reflect these changes without running the modified mesoscale model for the full sample of 366 days. The new map would then have to be validated again and possibly adjusted to address any remaining errors. This work fell outside the budget of this project. All objectives of this task were fulfilled.

4.0 Conclusions and Recommendations

4.1 Conclusions

This report has presented the results of a project designed to improve the understanding and characterization of the wind resources available in several promising wind energy development areas of California. The five selected focus areas represent a cross-section of meteorological and terrain types within different geographical areas of the state. Knowledge of the wind resources within these areas was improved through the application of advanced measurement, modeling, and mapping techniques.

The higher resolution modeling of the wind resource in the focus areas revealed more structure to the wind flow, as expected. In areas where mountain blocking and channeling are important, the new simulations increased the blocking effect and produced stronger flows through the passes. In other areas, the high-resolution runs produced more sheltering of the valleys by mountain peaks. Katabatic flows out of the mountains into valleys in northern California were moderately increased at the higher resolution. In two focus areas – San Gorgonio and Tehachapi – where enough data was available to validate the maps, the high-resolution runs produced a definite improvement in accuracy.

This project collected the first publicly available wind measurements using tall towers and complementary sodar technology targeting the 50 m - 200 m height interval, which is directly representative of today's large-scale wind turbines. A lesson learned during the screening process to select towers was that inordinate delays can occur when negotiating tower use agreements (and associated engineering studies) with the tower owners. The measurement program data enabled the boundary layer modeling research component but more data would have allowed for more comprehensive research and map validation in three of the focus areas (Mayacamas Mountains, Mojave, and Shasta).

The tower and sodar data enabled model versus observation comparisons that led to the identification of several modeling problems. The data also helped to determine the cause, and in some cases, the solution to the various problems. Boundary layer characterization can be improved by better accounting for atmospheric stability, terrain complexity, and surface energy budget formulation. Increased model resolution, use of the z-less scheme, and incorporation of better surface data (namely soil moisture and sea surface temperature) have the most beneficial impacts. Modeling in non-hydrostatic mode, the use of different mesoscale modes, the use of higher resolution initial condition data, or changing the stability scheme, offered little to no improvement.

The higher resolution map simulations in the Tehachapi area have been merged seamlessly into the statewide wind resource maps. The result is a somewhat greater concentration of the wind resource in a narrower band south of the Tehachapi Pass and Cottonwood Pass. The changes elsewhere are modest.

4.2 Commercialization Potential

Accurate wind resource assessment is a requirement for the siting and planning of a wind power plant. Improved resource assessment techniques, including wind mapping, can accelerate the site identification process at a reduced cost. Whereas previous development activity required one or more iterations of on-site wind assessment using meteorological masts to locate the best sites of interest, wind mapping allows project developers and government agencies to identify promising sites with greater certainty. Relatively small areas that may have gone unnoticed in the past are now also revealed through high-resolution mapping.

Wind mapping began in California decades ago with regional maps and the NREL National Wind Atlas. With the advent of new computer technologies and meteorological models, the wind map created by AWS Truewind under Contract #500-01-009 improved upon these initial products. This project represents an improvement over the statewide wind map released four years ago. Each step of the process has provided newer and better information to facilitate the commercial development of wind energy, for both large- and small-scale wind technologies.

This project addressed the PIER goal of improving the reliability and quality of California’s electricity by more accurately defining wind resources in the State and identifying areas of untapped or underdeveloped wind potential. This project also helped to improve energy cost/value of California’s electricity by providing better understanding of wind resources and helping to increase market penetration levels through the coupling of numerical modeling with advanced field measurements.

4.3 Recommendations

While atmospheric modeling techniques continue to improve, high-quality validation from on-site data continues to be essential. Therefore, additional field measurements are recommended, especially in non-developed areas of great potential such as the Mojave, the region northeast of the Tehachapi, and areas along the California – Mexican border. While the Mojave was selected as a focus area and other regions were identified in this project as candidate focus areas, the scope of this project did not provide for comprehensive data collection in most of the promising areas of future development. In particular, while a short-term sodar campaign was conducted in the Mojave, the area lacked a meteorological mast at or near hub-height mast with at least of year long period of record. A cost-effective approach to data collection in such areas would be the installation of industry-standard meteorological masts (50-60 m) at targeted locations within each area coupled with short-term sodar campaigns to characterize the shear and vertical velocity up to 200 m above ground.

In tandem with new measurement campaigns, the running of higher resolution atmospheric models with upgraded input databases (e.g., soil moisture, sea-surface temperature, etc.) will yield improved siting information in the form of advanced wind maps. These maps can be produced most cost-effectively when run for targeted focus areas and then blended into the master statewide wind map.

7.4 Benefits to California

This project encourages the development of wind energy in the State by helping companies and individuals identify promising wind project sites with enhanced accuracy compared with previously available information. This not only benefits individual project development, but medium- and long-term planning activities such as transmission upgrades, land-use reclassifications, and changes in statewide, regional and local permitting requirements benefit as well. The high-quality data collected from the several sites at heights above traditional meteorological masts will enable government agencies, companies and individuals to reduce the uncertainty of development in those focus areas. Finally, improved boundary layer modeling techniques provide more efficient plant siting as well as more accurate energy production predictions for proposed projects and production forecasting for commissioned projects.

Appendix

I Final Focus Area Selection Report
II Final Map Draft Comparison Report
III Final Detailed Measurement Program Plan
IV Final Boundary Layer Research and Findings Report
V Final Statewide Wind Maps and Modifications Report

I

Final Focus Area Selection Report

TrueWind Solutions

Final Report

TO: Michael Kane and Dora Yen
FROM: Bruce Bailey and Michael Brower
DATE: February 6, 2004
RE: Task 2 Final Focus Area Selection Report and Final List of Candidate Focus Area Sites
Contract No. 500-03-006

This transmittal constitutes two of the four deliverables for Task 2 (Selection of Focus Areas) of the Energy Commission project "Wind Energy Resource Modeling and Measurement." The first deliverable—Final Focus Area Selection Report—discusses the criteria and methods used for selecting focus areas, while the second deliverable—Final List of Candidate Focus Area Sites—identifies the location of the candidate areas.

Focus Area Selection

The selection objectives for the focus areas are laid out in the contract's scope of work:

- The areas should offer significant promise for wind energy development after considering important siting factors.
- Two areas should be within the major, known wind resource areas of the state.
- The remaining three areas should be relatively unexplored and offer the potential for new, large-scale project development.
- The focus areas should represent a variety of terrain in order to adequately test the wind modeling process. One focus area should contain a mountain pass.
- The focus areas should also investigate regions of particular interest to the Energy Commission. One of the areas should be in Northern California. Another should be in the Mojave Desert.

It is also desired that tall towers exist within or near the focus areas so that the meteorological measurements activities of Task 4 can be co-located.

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The selection of candidate focus areas was a four-step process:

1. A geographical information system (GIS) was used to screen the state for suitable development sites by selecting and applying several siting criteria having an important bearing on project feasibility and economics, including:
    - ◊ Wind resource as defined by the CA wind map developed by TrueWind for the Energy Commission
    - ◊ Elevation and air density
    - ◊ Proximity to transmission
    - ◊ Proximity to populated areas
    - ◊ Exclusion of park lands, wilderness areas and conservation areas
    - ◊ Exclusion of water bodies
    - ◊ Exclusion of steeply sloped terrain (>15%), which is generally not negotiable by heavy trucks carrying large turbine equipment components.

    Using a cost-based approach, proprietary algorithms developed by TrueWind were then applied to identify the most cost-effective sites able to support project sizes of at least 50 MW. This approach used capital and construction cost assumptions for wind plants and for roads and transmission lines (including substations), which accounted for distances from existing facilities. Wind plant capacity factors were calculated by matching wind map-derived resource statistics with a generic turbine power curve reflecting current megawatt-scale wind technologies.

2. Following a review of the GIS-based site screening exercise, 22 candidate focus areas were chosen to satisfy the established selection objectives. The candidate areas were then classified into nine categories based on landform type, geography, and experience with prior wind development:
    - ◊ A – Along California-Mexico border (2 areas)
    - ◊ B – Desert areas (6 areas)
    - ◊ C – Existing San Gorgonio wind farms (1 area)
    - ◊ D – Existing Tehachapi wind farms (4 areas)
    - ◊ E – Coastal mountain sites (3 areas)
    - ◊ F – Existing Altamont Pass wind farms (1 area)
    - ◊ G – Existing Solano County & Montezuma Hills wind farms (2 areas)
    - ◊ H – Interior ridgeline sites (2 areas)
    - ◊ I – Northern valley site (1 area)

    Only one area is to be selected from any one category. Some of the final focus areas sites may be a combination of multiple initial candidate focus area sites of the same category. Two areas are to represent existing project development areas (categories C, D, F & G).

3. A tall-tower search scheme was applied to the 22 candidate focus areas to determine which candidate focus areas met the requirements of the meteorological measurement activities of Task 4. This scheme utilized the FCC Antenna Structure Registration, the

FAA Digital Obstacle File, site visits, as well as communications with tower owners and local contacts.

4. The results of the first three steps of the selection process were compiled and evaluated, resulting in the selection of the final candidate focus area sites.

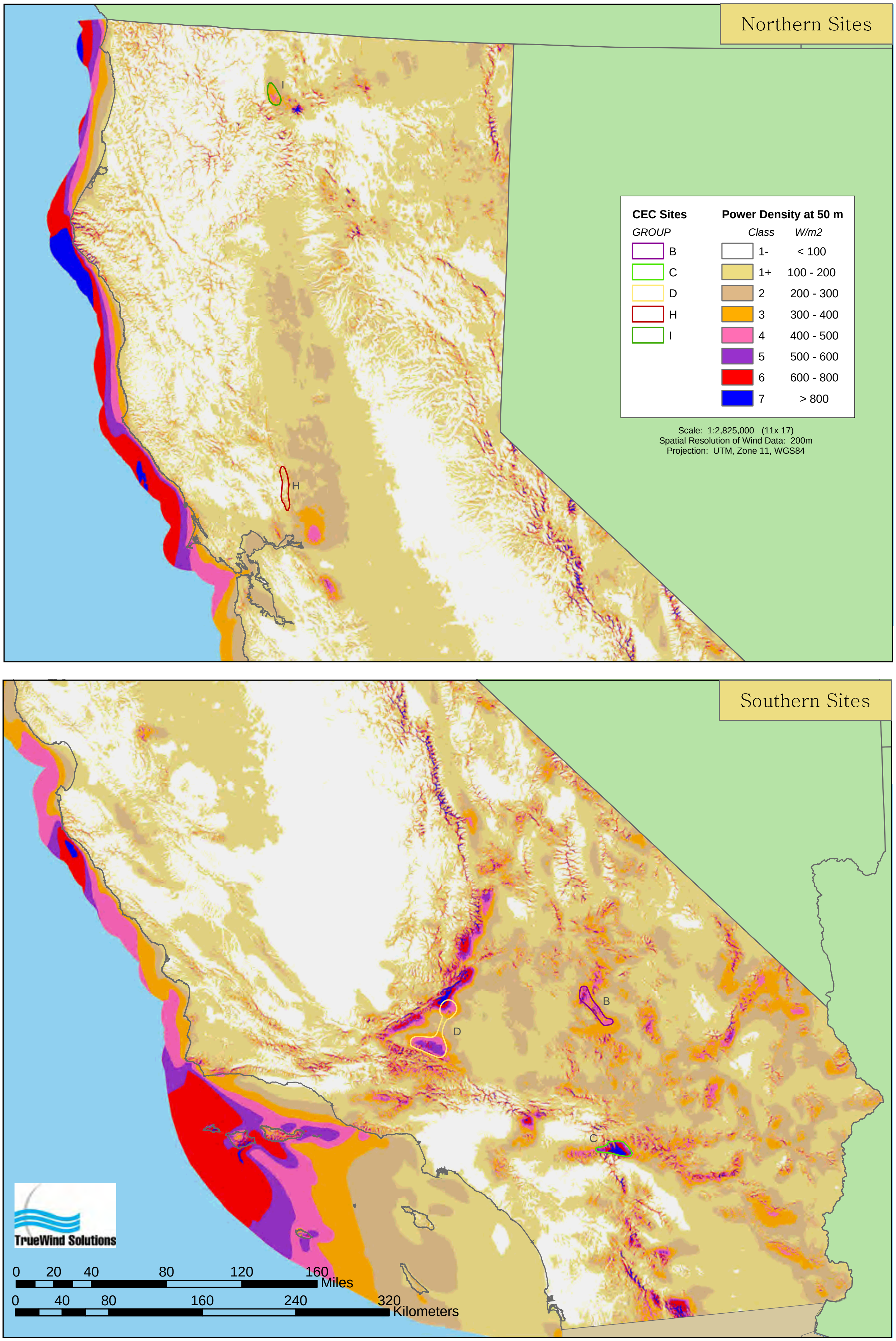
Final List of Candidate Focus Areas

A separate Excel spreadsheet lists the final candidate focus area sites with their corresponding counties and centroid coordinates (lat/long and UTM). In addition, locations of the focus area sites were drawn on the base wind map of the state. Both the list and map (in .pdf format) were submitted separately from this report.

Final List of Candidate Focus Area Sites for the Energy Commission "Wind Energy Resource Modeling and Measurement" Project
TrueWind Solutions, LLC

Site	Group	Description	County	Lon_Centroid	Lat_Centroid	X_Centroid	Y_Centroid
				DD, WGS84		UTM Zone 11, WGS84	
B	B	Desert areas	San Bernardino	-116.83155	35.03514	515379.00537	3876946.68771
C	C	Surrounding existing San Gorgino wind farms	Riverside	-116.62582	33.93259	534583.13781	3754746.83486
D	D	Surrounding existing Tehachapi wind farms	Los Angeles/Kern	-118.30435	34.81656	380687.99089	3853458.96654
H	H	Ridge line sites	Sonoma/Lake/Napa	-122.66575	38.69379	7123.21269	4298058.61262
I	I	Northern site	Siskiyou	-122.44268	41.51182	45739.71433	4609896.98477

Map of Final Candidate Focus Areas



II

Final Map Draft Comparison Report

WIND ENERGY RESOURCE MODELING AND MEASUREMENT PROJECT

DRAFT MAP COMPARISON REPORT

Task 3: Focus Area Mapping

Contract No. 500-03-006

Submitted by:

TRUEWIND SOLUTIONS, LLC

(now *AWS Truewind LLC*)

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August 10, 2004

WIND ENERGY RESOURCE MODELING AND MEASUREMENT PROJECT

DRAFT MAP COMPARISON REPORT

TASK 3: FOCUS AREA MAPPING

The overall goal of this project is to improve the accuracy of wind resource estimates in promising areas of the State of California by addressing three key issues: the resolution of the original mesoscale and microscale model runs; the structure and modeling of the boundary layer; and measurements from tall towers and sodar. This report summarizes progress to date on Task 3: Focus Area Mapping, which seeks to address the first of the three issues.

1 Background

In Task 2 of the project, five promising areas of the state for wind energy development were selected for further study. The five areas are denoted as follows:

Group	Description	County
B	Desert areas	San Bernardino
C	Surrounding San Gorgonio wind farms	Riverside
D	Surrounding Tehachapi wind farms	Los Angeles/Kern
H	Ridgeline sites	Sonoma/Lake/Napa
I	Northern valley site	Siskiyou

A map of the five focus areas overlaid on the California wind power map is attached.

The immediate goal of Task 3 was to investigate the effect of model resolution on the wind resource in the five areas, with the ultimate aim of producing a more accurate wind resource map. Model resolution – expressed usually as the spacing between individual grid points in the simulations - is an important parameter because it affects how well the model can capture the influence of topography and variations in surface characteristics (such as roughness). In the California wind passes, in particular, we suspected that our mesoscale model, MASS, was unable to fully resolve mountain blocking and channeling effects, which have a large influence on the wind resource both along ridgelines of the coastal mountains and in the main wind resource passes of the state. The importance of mesoscale resolution is a reflection of California's unique wind climate. In late spring and summer, a powerful but shallow flow develops on a daily basis as a result of the contrast between the hot desert interior and relatively cool ocean. This flow traverses the coastal mountains mainly through gaps or passes. The strength of the flow is heavily influenced by factors such as the height of the surrounding mountains and the width of the pass. Without adequate resolution, the mesoscale model "thinks" the mountains are less high and the pass is less wide (or completely invisible to the model), and therefore it can underestimate the wind speed through the passes and overestimate it over the mountain peaks.

An additional factor is the resolution of the microscale model, WindMap, which affects the degree of acceleration over small hills and ridges embedded within a larger flow pattern.

However this effect is of much less importance than the mesoscale model resolution, as it is the mesoscale model that simulates the driving forces of the California wind climate.

2 Procedure

The MASS resolution used to create the original California wind map was 2 km, while the WindMap resolution was 200 m. In Task 3, we halved the MASS grid spacing to 1 km and halved the WindMap grid spacing to 100 m. The resulting wind speed maps are shown in the appendix and are discussed below.

2.1 Area B: Mojave Desert

Area B is located in the Mojave Desert in San Bernadino County near the city of Barstow. It was chosen because it contains typical examples of desert mesas, mountains, and passes, many of which are predicted to have a good wind resource (at least 7 m/s mean speed at 50 m). There are also numerous transmission lines crossing the area.

The high-resolution focus area wind speed map at 50 m is shown in Figure 1. A map showing the changes between this new map and the old (expressed as a ratio of mean speeds at 50 m) is shown in Figure 2.

The most striking feature of the ratio map is the zone of >10% increase in mean speed in the middle, which is centered on dry Coyote Lake. This area is in the outflow from a gap between the Calico Mountains and Lane Mountain to the west. This suggests that at a higher resolution, the model simulates more channeling through the gap. Despite the increase in average speed, however, the predicted wind resource in the area is modest, with a mean speed of about 5 m/s. There is a similar but smaller increase in wind speed at the eastern edge of the area. This appears to be another outflow zone formed by a gap, this one between the lower end of the Calico Mountains and Calico Peak. Once again, the predicted mean speed is modest.

By contrast, the large area of channeled flow through the Mojave Valley (through which I15 and I40 pass) is relatively unaffected by the higher mesoscale resolution, except to be extended somewhat farther to the east. This indicates that the original mesoscale resolution was sufficient to resolve this pass, but not the other two, smaller passes. The mean wind speed through the Mojave valley is predicted to be 6.5-7 m/s at 50 m height, a moderate but potentially attractive wind resource.

The pattern of change in the mountains is a good deal more complex. Although it is difficult to tell in these maps, the predicted wind speed along the ridgelines, by and large, increases by 5-10% compared to the original map. At the same time, the predicted speed just off the ridgelines is predicted to be lower. This is to be expected where the predominant effect of the higher resolution is to raise the peaks and steepen the slopes of the mountains. It is significant, however, that an increase in the blocking effect at the mesoscale, if it occurs, is not enough to offset the effect of sharper terrain at the microscale.

There is, unfortunately, limited data with which to validate the map changes. The one station in an area of significant change is a proprietary mast on a peak in the southern part of the area. The original map appeared to underestimate the wind speed at 50 m by about 10%. The new map appears to overestimate the speed by about 4%. There is not enough data with to draw firm conclusions, however.

2.2 Area C: San Gorgonio Pass

Area C, San Gorgonio Pass, was chosen because of the large concentration of wind projects in the area, and the potential for additional projects, as well as for the availability of considerable amounts of wind data, which can be used to verify the maps.

The high-resolution focus area wind speed map at 50 m is shown in Figure 3, and a map showing the ratio between the new map and the old is shown in Figure 4.

The ratio map shows an area of increased speed through the middle and particularly out the eastern end of the pass, and also extending southeast into the Coachella Valley. This is not surprising because of the ability of the MASS model to better resolve the pass and its outlet at the higher resolution. Once again, in the mountains, there is a more complex pattern of increases and decreases, with most ridgelines experience a moderate increase in the predicted wind speed.

To test whether the higher resolution helps to improve the accuracy of the model predictions, we compared both the original (unadjusted) and new maps with validation data from 18 stations gathered in the first project. We found that the original, unadjusted map was, on average, about 1.1 m/s below the measured speed extrapolated to 50 m, while the standard deviation between the map and data was 1.3 m/s. After the high resolution runs, however, the average bias was -0.65 m/s and the standard deviation was 1.0 m/s. Thus, there was a clear improvement in accuracy of the map. This is also evident in a scatter plot of the observed and predicted values, shown below. The r^2 value rose from 0.47 to 0.68 with the higher resolution.

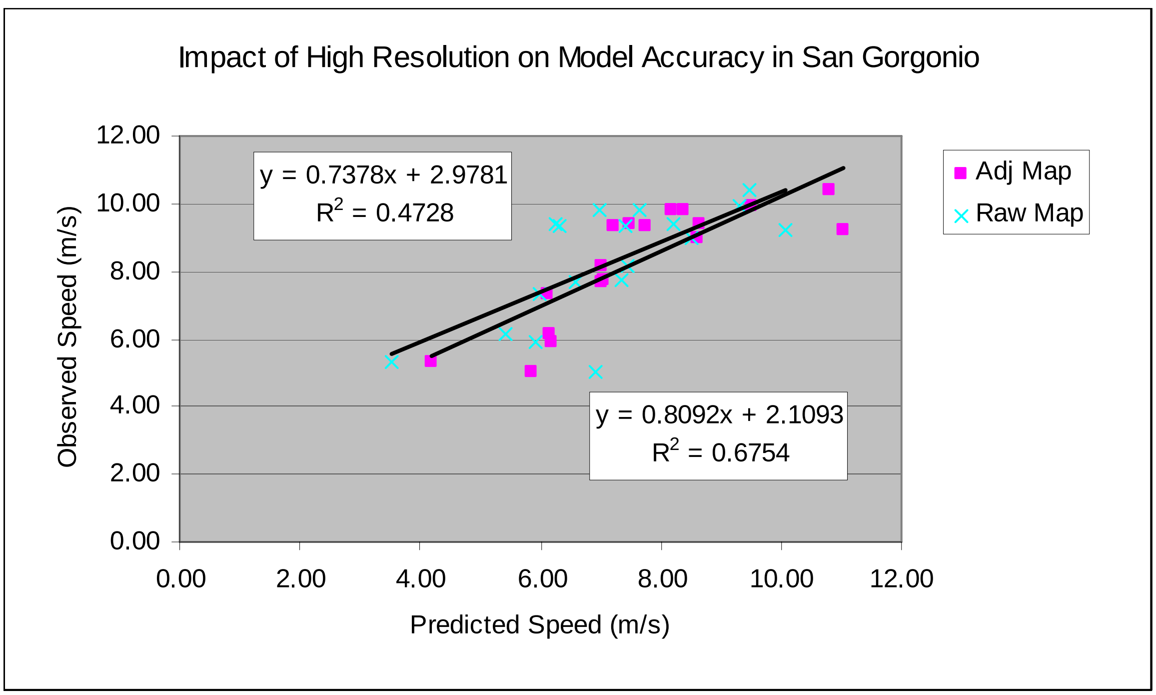

Figure 5. Comparison of predicted and measured/extrapolated data for 18 stations in the San Gorgonio Pass area. The raw map (upper trend line) represents the results of the original wind mapping project, without adjustments. The adjusted map is the result of the high-resolution runs. Note the increase in r^2.

We also found that the adjustments applied to the raw map in the first project were quite similar to the changes resulting from the higher resolution. In fact, the error statistics (average bias and standard deviation) for the original map after the adjustment were about the same as those of the high-resolution map. Thus, the original adjustment captured the effects of higher resolution with some skill.

However, it should also be noted that there are significant remaining discrepancies between the map and data. Other research we have carried out (reported elsewhere) suggests at least part of the remaining discrepancy may be due to incorrect soil moisture assumptions in the mesoscale simulations, which result in an incorrect pattern of surface heating and cooling.

2.3 Area D: Tehachapi Pass

The high resolution speed map of Tehachapi Pass and the map of the ratio of the new to old speeds are shown in Figures 6 and 7.

As there is in Area B, there is a clear pattern of significant increase within and downwind of several passes, most importantly Tehachapi Pass, but also two others, the one to the south known as Cottonwood, and the other to the north, Lone Tree Canyon. The increased wind resource out of Tehachapi Pass extends well out onto the valley floor. Why this occurs, both here and in Area B, is a matter for further study.

Accompanying the increase in the wind resource in the passes, there is a decrease downwind of the higher parts of the Tehachapi Mountains. This is to be expected, given that, with higher resolution, the MASS model simulates greater blocking of the shallow flow by the mountains, and correspondingly greater flow through the passes.

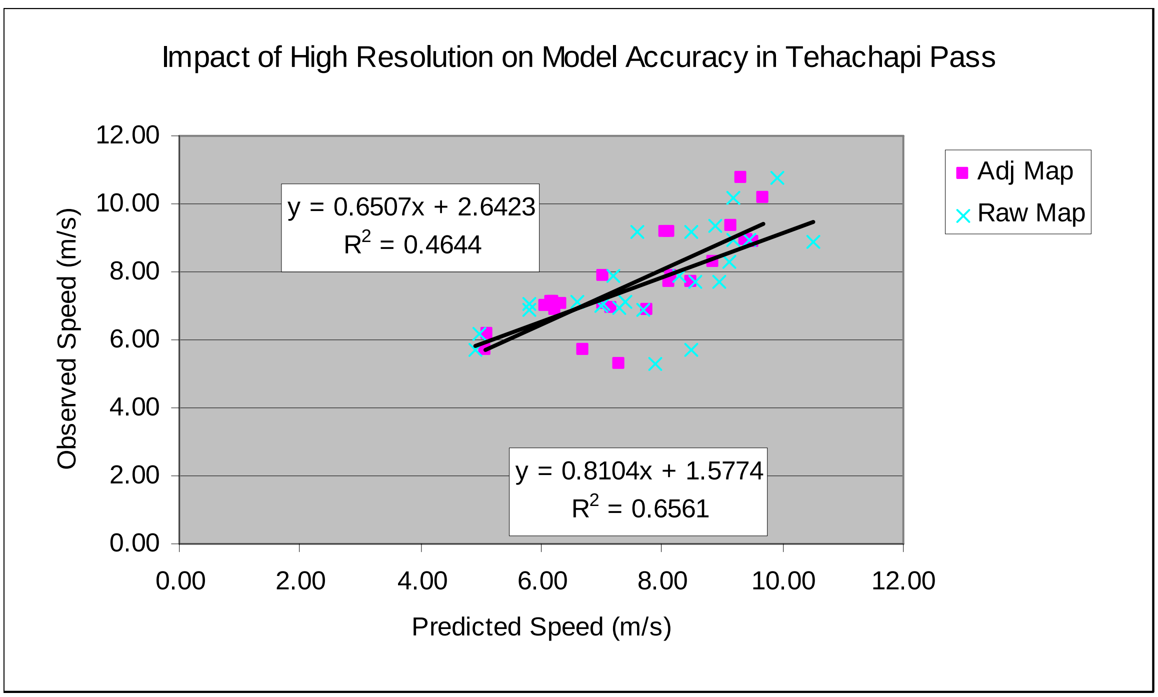

Figure 8. Comparison of predicted and measured/extrapolated data for 25 stations in the Tehachapi Pass area. The raw map (shallower trend line) represents the results of the original wind mapping project, without adjustments. The adjusted map (steeper trend line) is the result of the high-resolution runs. Note the increase in r^2.

Once again, we compared the results with the validation data (25 stations) and found some improvement. The original (unadjusted) wind map had very little bias overall (about 0.1 m/s), but the standard deviation between the data and map was 1.15 m/s. With the high-resolution map, the bias remains small (-0.1 m/s), and the standard deviation is reduced to 0.87 m/s. The scatter plot in Figure 8 reveals the improvement as a tighter fit between the model and data and a higher r^2 value.

The resulting accuracy improvement is comparable to that obtained in the adjustments to the original map. However, unlike the case of San Gorgonio Pass, the pattern of changes is quite different. In fact, while the correlation between the original map adjustments and the impact of higher resolution in San Gorgonio Pass is significantly positive (about 0.5), the correlation between the two in Tehachapi is slightly negative (-0.2). In other words, both the original adjustments and the higher resolution model runs improved the results, but in different ways.

The original adjustments, were, of course, based on the observed map errors, and thus (unless the data were wrong) we must conclude that whatever problems with the simulations caused the errors in those locations, they have nothing to do with the model resolution. Conversely, the changes wrought by higher resolution have improved the fit to the data in ways that were missed in the original validation and adjustment process.

Incidentally, combining the original adjustment with the higher resolution runs results in a standard deviation between map and data of 0.67 m/s, just over one half the standard deviation between the original map and data.

2.4 Area H: Ridgeline

Area H, which covers portions of Sonoma, Lake, and Napa counties, was selected for study as a typical example of a coastal mountain ridgeline, one that may offer some attractive sites for wind energy development because of its moderately good wind resource (predicted to reach about 7-8 m/s in places) and proximity to the transmission grid. The high resolution speed map of Area H and the map of the ratio of the new to old speeds are shown in Figures 9 and 10.

The ratio map presents a rather complicated picture. The average change in mean speed across the whole region is about -6%, i.e., a moderate decrease. This is probably mainly because of increased sheltering of the valleys in the high-resolution simulations. There are a few exceptions - broad valleys which, perhaps because of their orientation to the prevailing wind, are predicted to have a somewhat greater wind resource than in the original wind map.

Within the mountains, the impacts of higher resolution are too complicated to be easily interpreted. Most of the variations in the speed ratio are on too small a scale to have anything to do with the mesoscale model. Rather, they reflect small differences in elevation at the microscale. The impact is particularly noticeable on sharp mountain peaks, where slight changes in elevation due to the change in resolution can result in substantial changes in the predicted wind speed.

A close examination of the main ridgelines – which are the only areas in the region with a potentially attractive wind resource – reveals a slight decrease in the maximum predicted wind speed. This is to be expected since, at a higher resolution, the mesoscale model is able to simulate more mountain blocking. The impact, however, is quite modest – typically a few percent, or 0.1-0.3 m/s.

Unfortunately, we have data for only two stations in this area, one at the Geysers and the other at Mt. St. Helena, which is not enough to confirm an improvement in accuracy. The original map compared rather well to the data at these two stations, and there is no significant change with the new map.

2.5 Area I: Northern Valley

Area I was selected for study because it offers an interesting case study of mountain-valley interactions in northern California. Although the predicted wind speed in the region is generally low, except on the high peaks (especially Shasta Mountain, in the southeast corner), the predicted wind power density is moderately good (300-400 W/m^2) in places, particularly on the west side of the Shasta Valley and the northwest slope of Shasta Mountain. The contrast between the wind power and wind speed patterns is indicative of a highly variable wind resource. At certain times of day and certain times of year, the winds in these areas may be very strong, whereas they are probably moderate or weak at most other times. The likely mechanism for the strong winds is a mountain-valley circulation created by differential heating of the valley and mountain slopes. In a typical scenario, the valley is warmed by the sun much more than the mountain slopes are. The warm valley air rises, and the cold mountain air rushes down to take its place.

The high resolution speed map of Area I and the map of the ratio of the new to old speeds are shown in Figures 11 and 12. As with Area H, the ratio map presents a complicated picture. Focusing, however, only on the areas just mentioned, it appears that higher resolution has enhanced the predicted outflow from the mountains, particularly on the west side of the valley. Unfortunately, we do not have data from stations in these areas to confirm whether the predicted wind resource is accurate, nor whether the higher resolution has improved the accuracy of the map.

3 Summary and Conclusions

We have produced high-resolution wind resource maps of the five focus areas. The impact of the high resolution on the model results, though difficult to interpret in some cases, generally follows our expectations. In areas where mountain blocking and channeling are important, the higher mesoscale model resolution has increased the blocking effect and produced stronger flows through the passes. In other areas, the high-resolution runs produce more sheltering of the valleys by mountain peaks. Katabatic flows out of the mountains into valleys in northern California appear to be moderately increased at high resolution.

In the two regions – San Gorgonio Pass and Tehachapi Pass – where we have enough data to validate both the original and new maps, the high resolution runs have produced a definite improvement in accuracy. The standard deviation between the map and observed wind speeds dropped in both cases by about 25%, while the degree of correlation (r^2) between the map and data increased from about 0.46 to 0.65. Since errors in the data contribute to the standard deviation, the actual improvement in map accuracy is probably greater than these figures suggest.

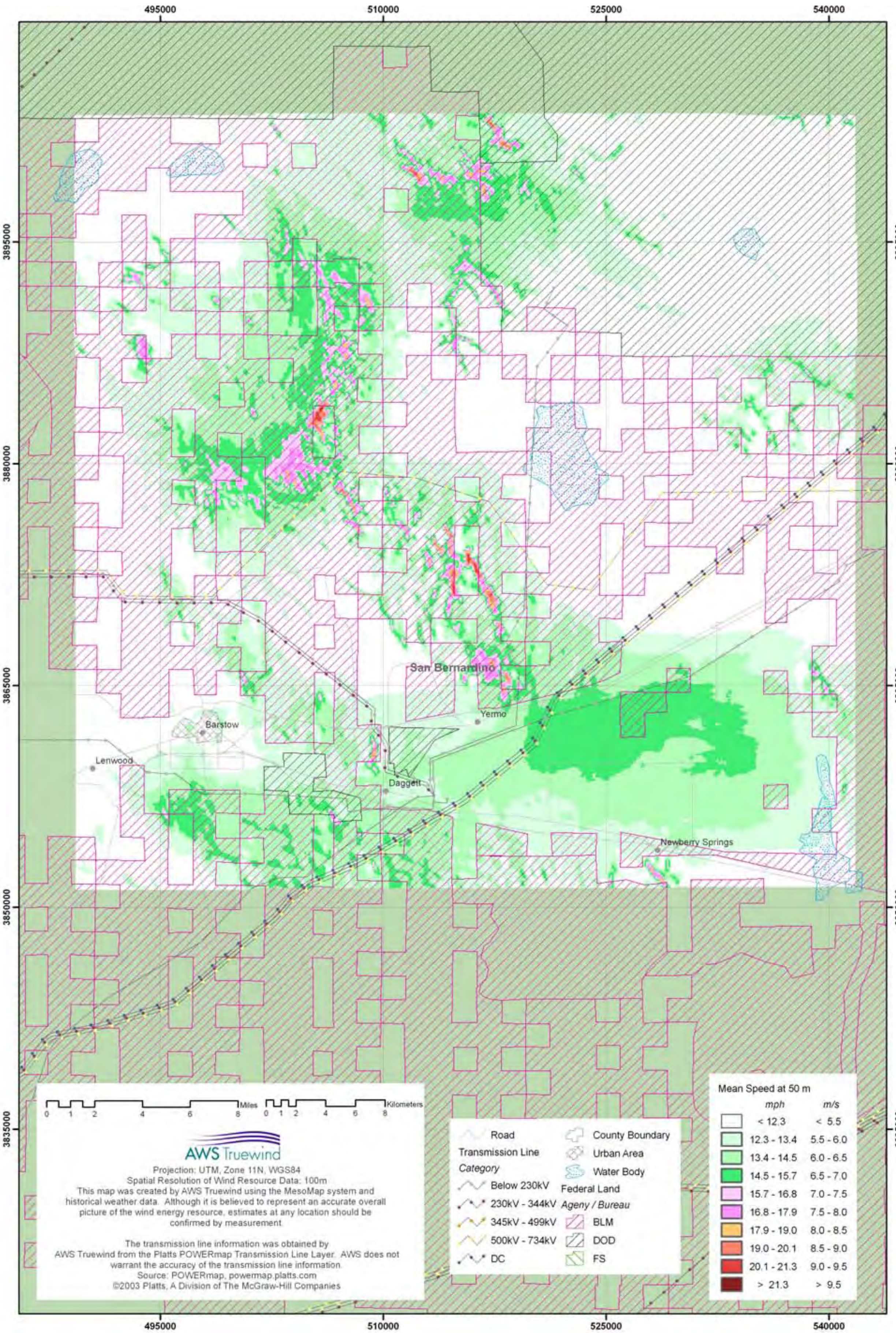

Figure 1: Wind Speed Map at 50 Meters, Focus Area B – Mojave Desert

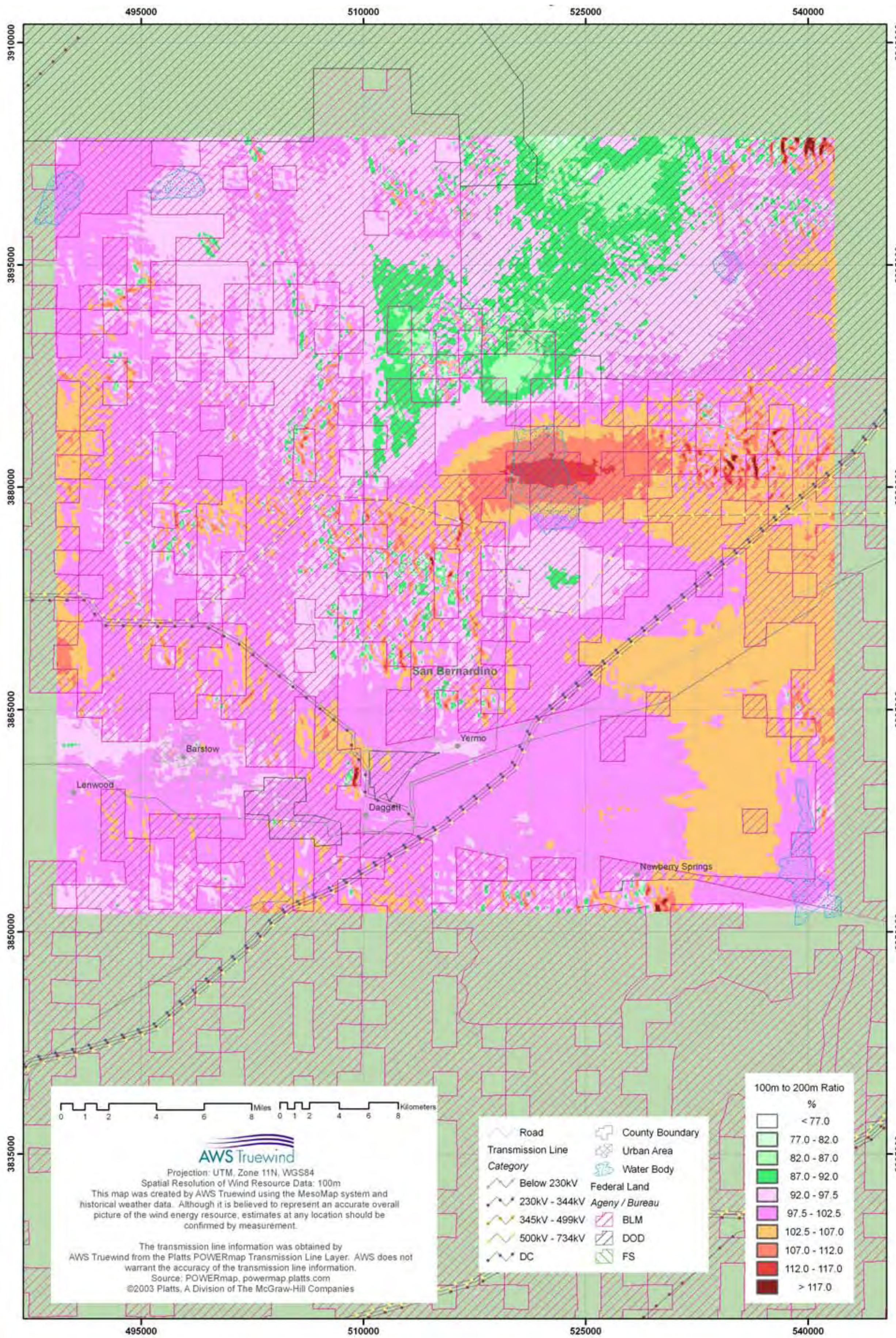

Figure 2: Percent Change in Wind Speed at 50 Meters, Focus Area B – Mojave Desert

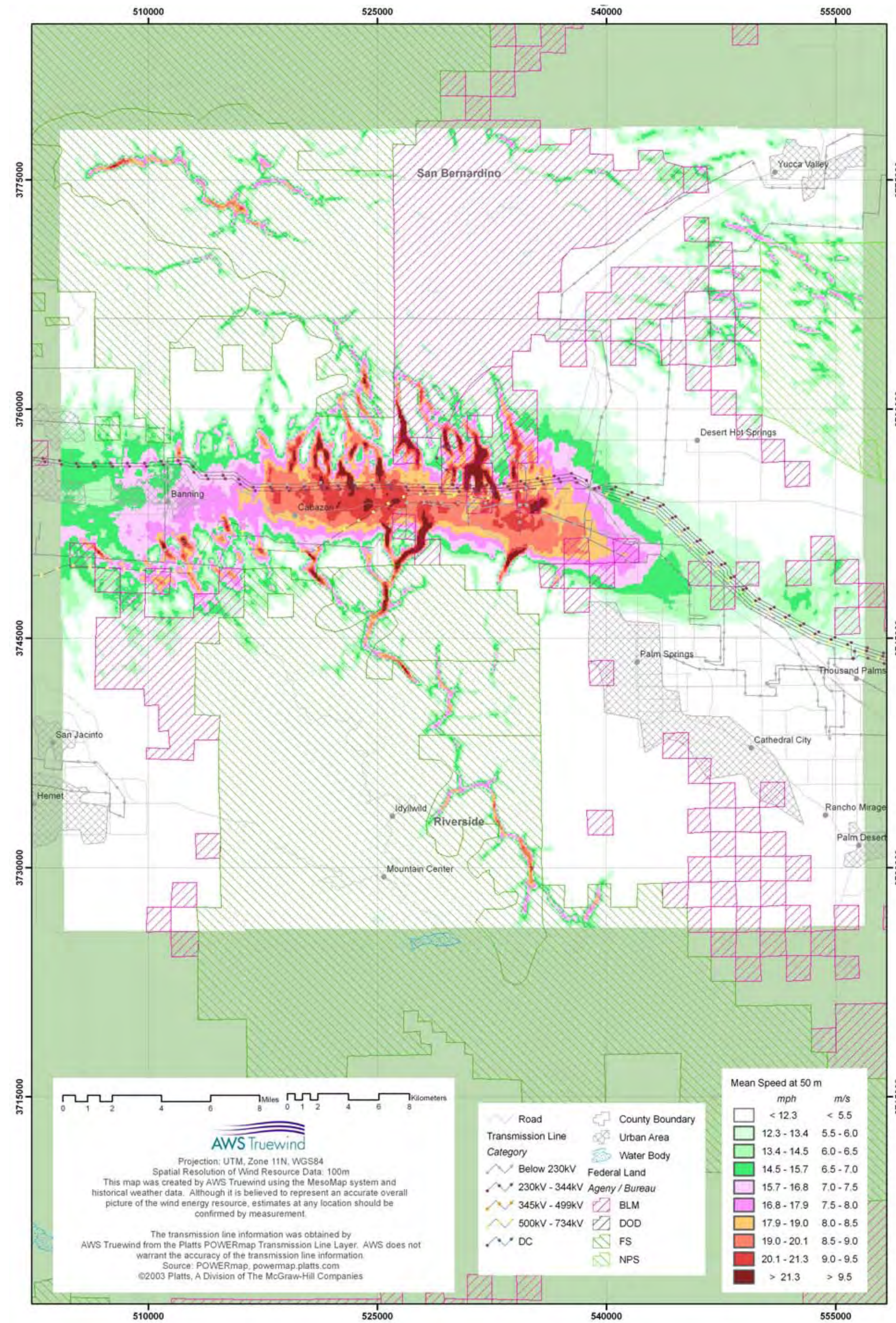

Figure 3: Wind Speed Map at 50 Meters, Focus Area C – San Gorgonio Pass

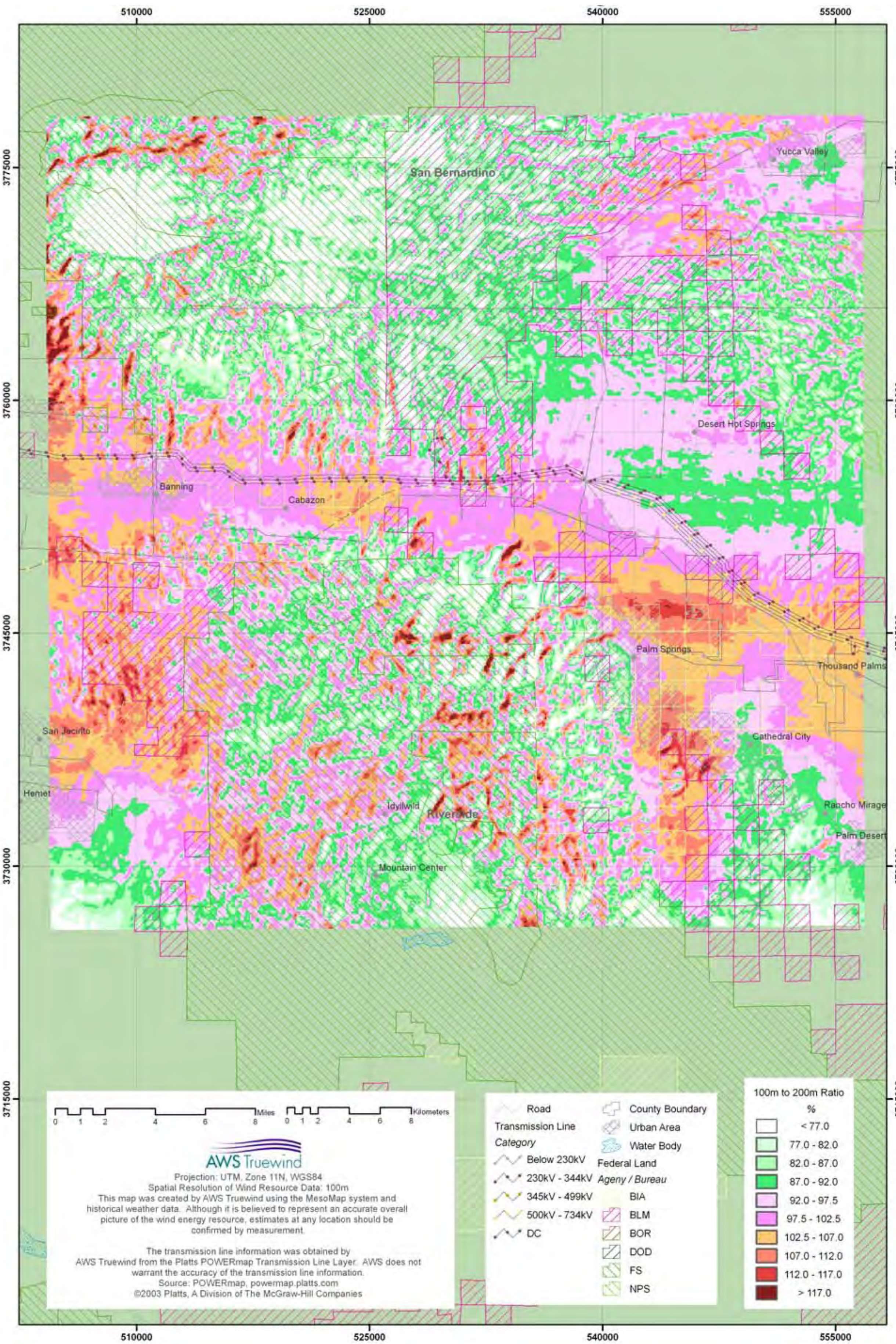

Figure 4: Percent Change in Wind Speed at 50 Meters, Focus Area C – San Gorgonio Pass

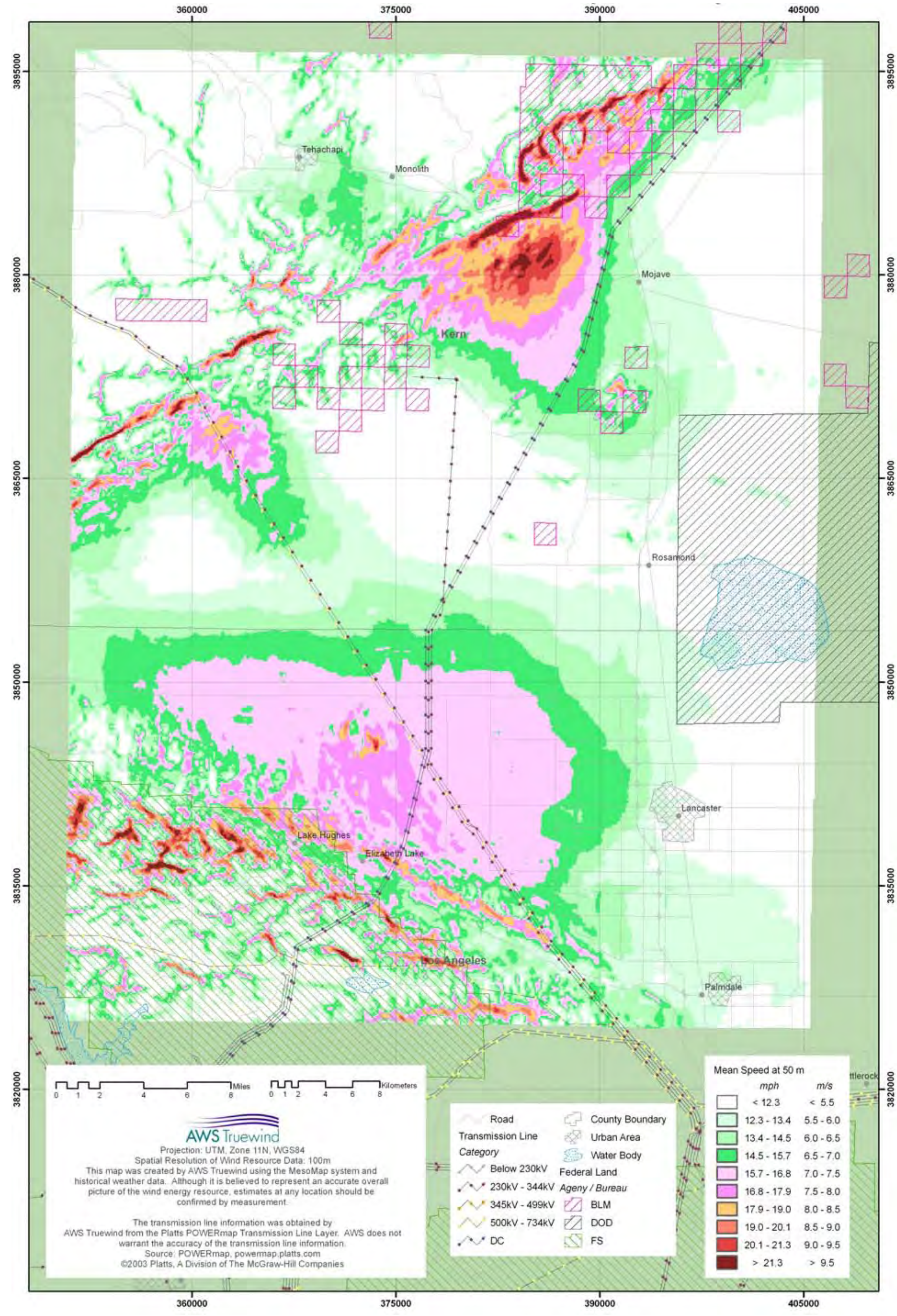

Figure 6: Wind Speed Map at 50 Meters, Focus Area D – Antelope Valley

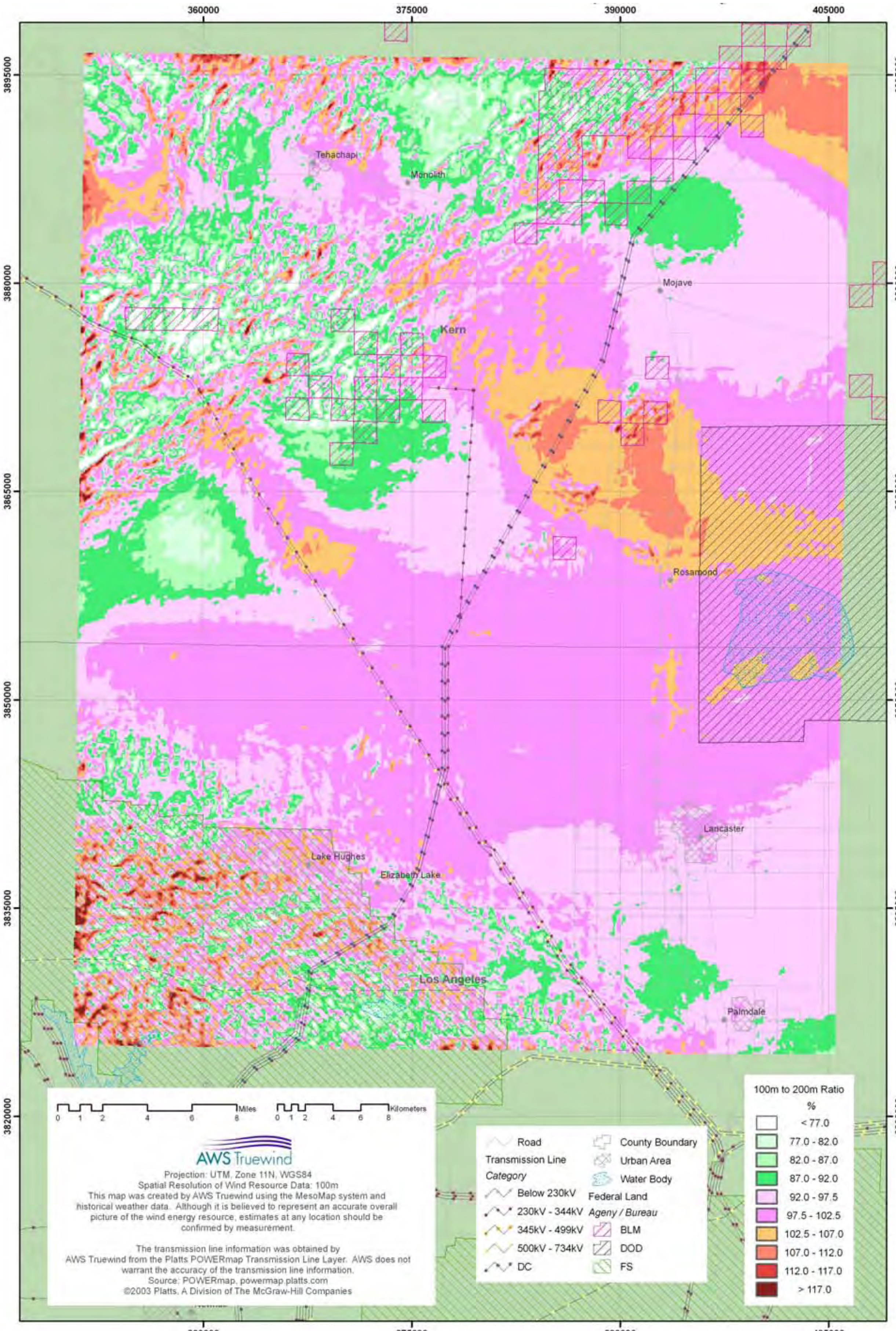

Figure 7: Percent Change in Wind Speed at 50 Meters, Focus Area D – Antelope Valley

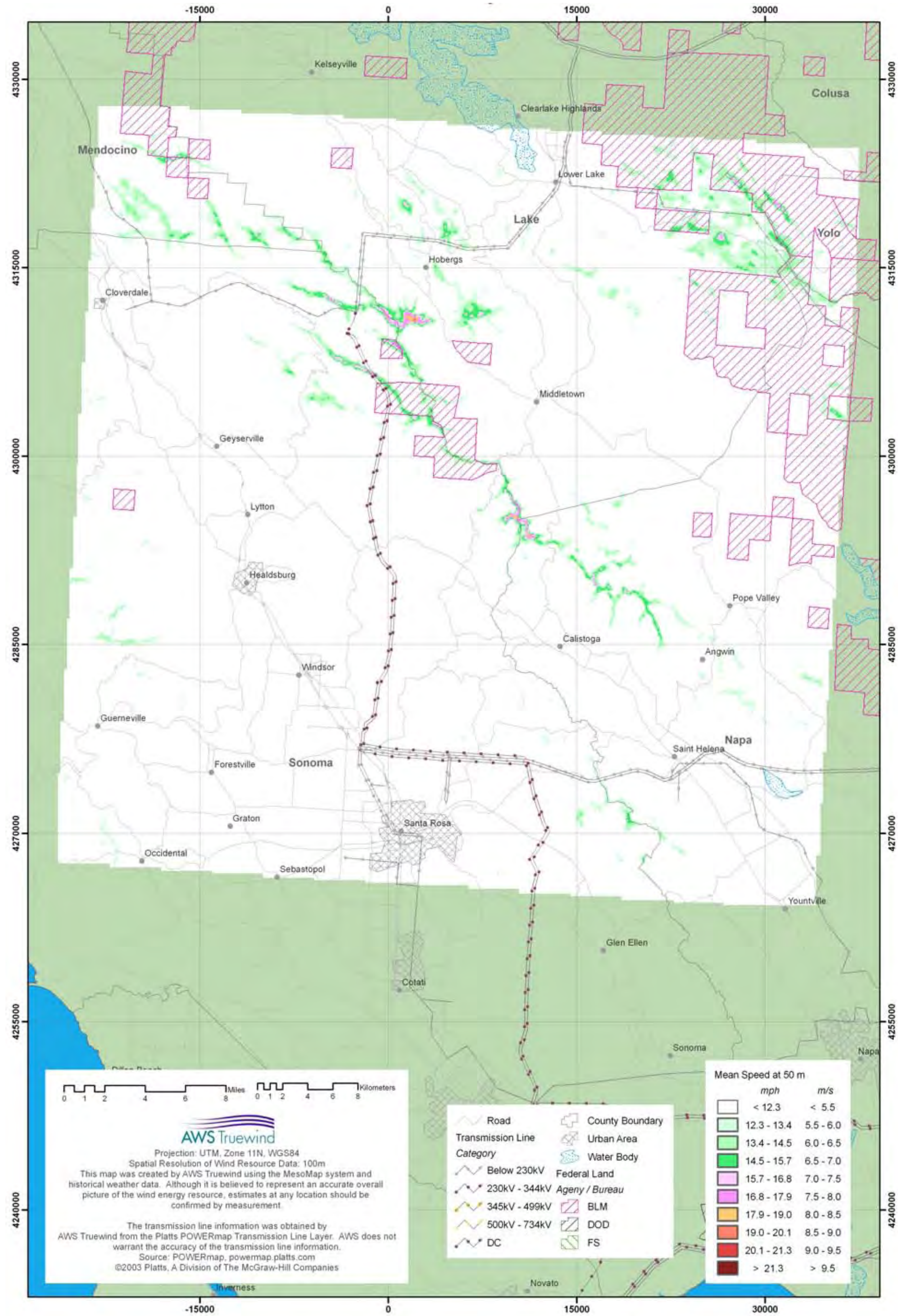

Figure 9: Wind Speed Map at 50 Meters, Focus Area H – Mayacamas Mountains

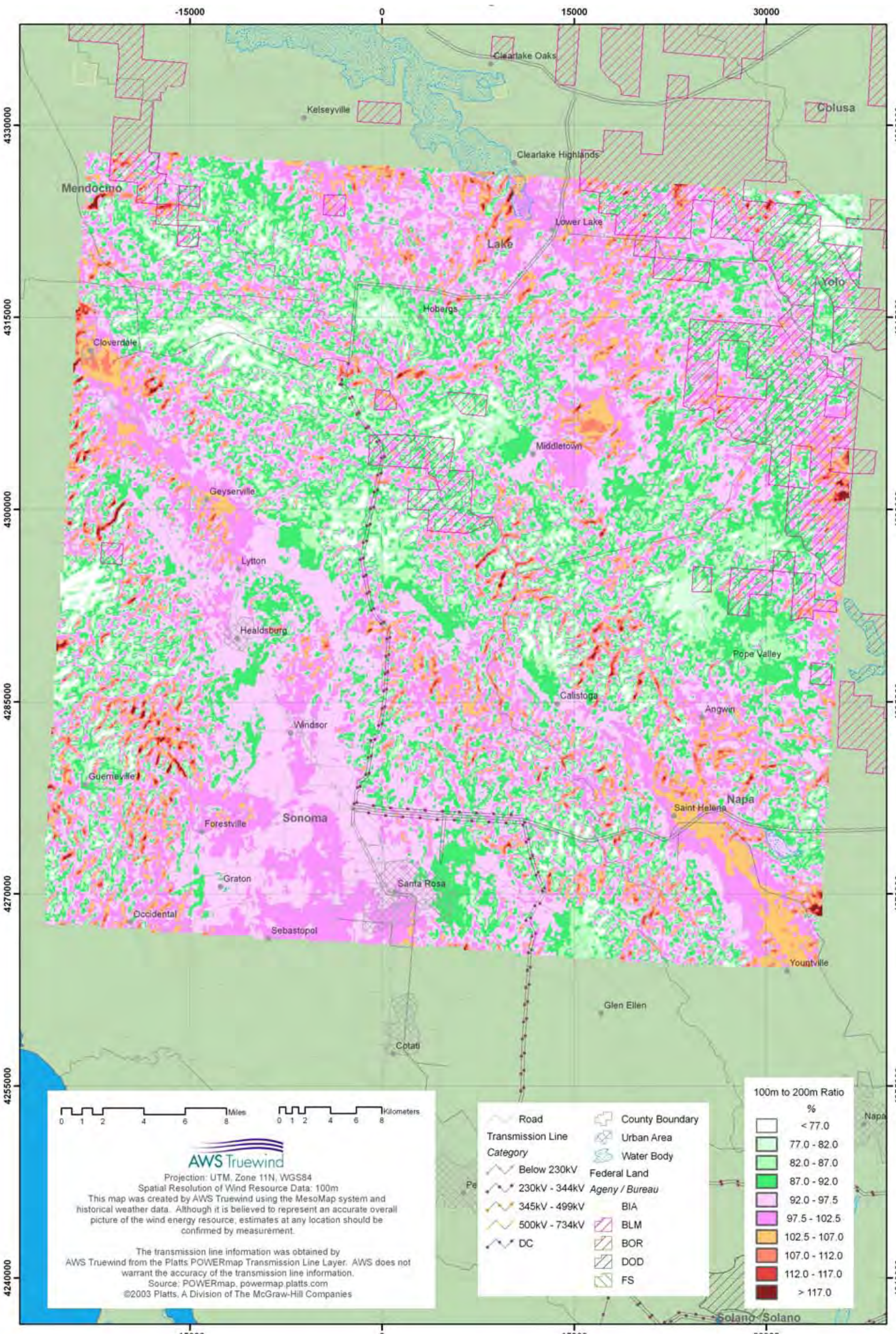

Figure 10: Percent Change in Wind Speed at 50 Meters, Focus Area H – Mayacamas Mountains

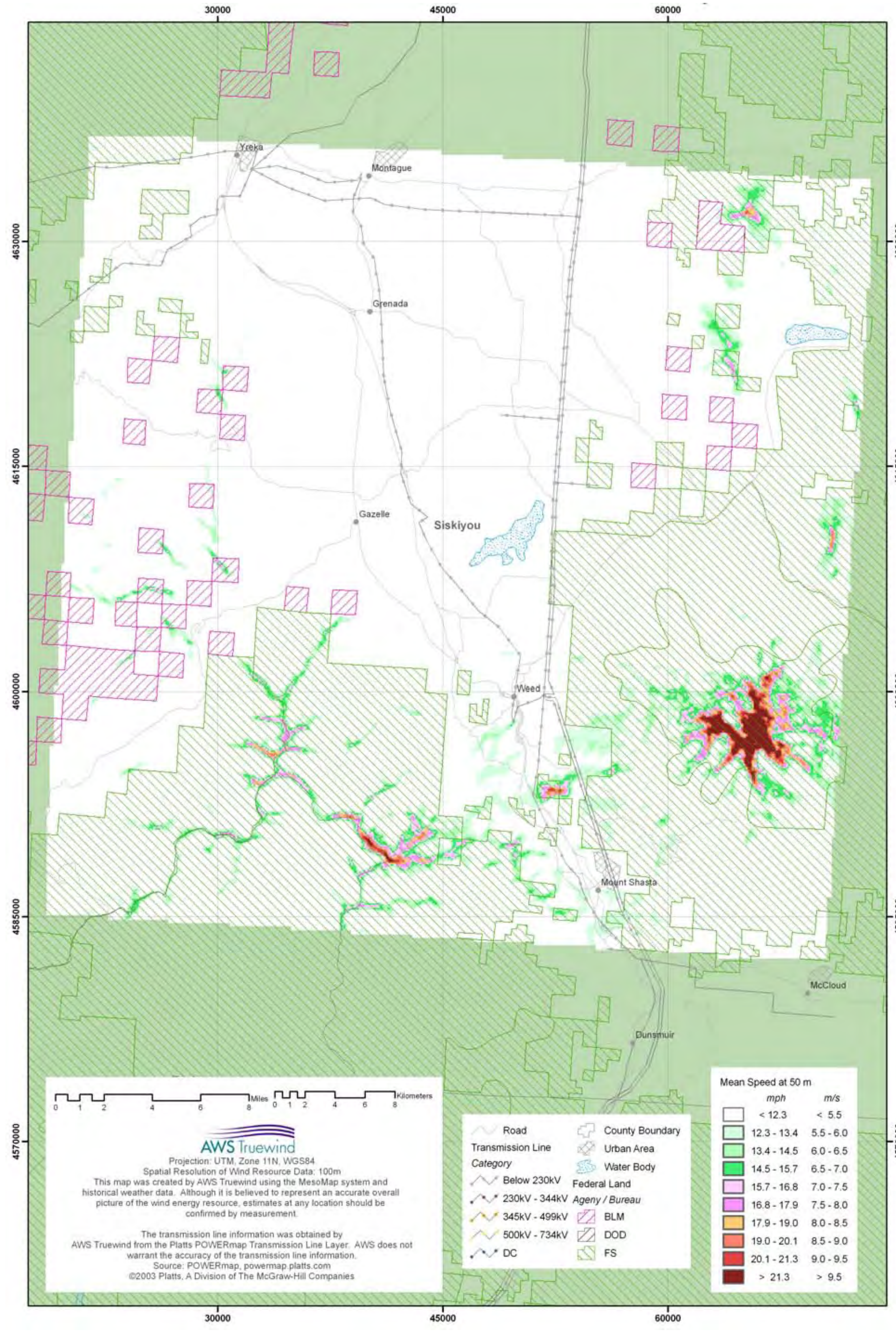

Figure 11: Wind Speed Map at 50 Meters, Focus Area I – Shasta Valley

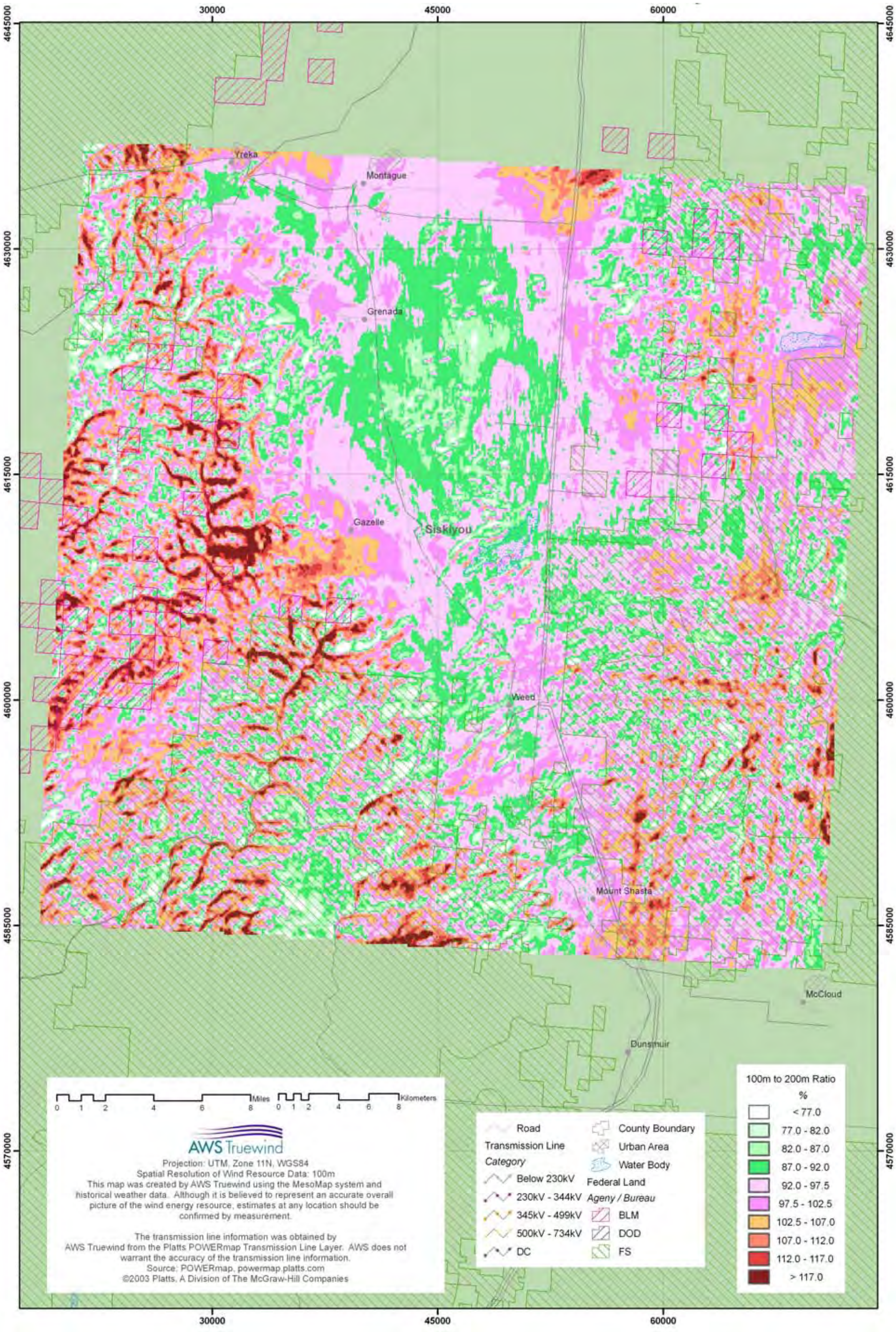

Figure 12: Percent Change in Wind Speed at 50 Meters, Focus Area I – Shasta Valley

III

Final Detailed Measurement Program Plan

Final

Detailed Measurement Program Plan

Prepared by TrueWind Solutions, LLC
Albany, New York

for

California Energy Commission

Sacramento, California
Contract No. 500-03-006

June 30th, 2004

Task 4: Measurement Program

Objective

The fundamental goal of the measurement program is to improve the understanding of the atmospheric boundary layer to heights of relevance for modern wind turbines (up to 150 m). This collected data will be used to refine wind resource estimates for particular focus areas throughout the state. In addition, the data may be used to improve the modeling of the boundary layer, and hence the accuracy of model estimates elsewhere in the state.

Background

This document is the Final Detailed Measurement Program Plan, hereon referred to as the Final Plan. The Final Plan was developed by TrueWind Solutions, hereon referred to as TrueWind, to guide Task 4 of the Wind Energy Resource Modeling and Measurement Project, contact number 500-03-006, with the California Energy Commission. The California Energy Commission will be referred to as the Commission from this point forward.

Test Plan Approval

The Final Plan is submitted following the submission of the Draft Plan to the Commission. Time was allocated after the submission of the Draft Plan for the Commission to review and comment on the Draft. The Commission requested that the Final Plan further detail the SODAR campaign. In response, the Draft SODAR Deployment Plan was generated and submitted to the Commission. The Final Plan incorporates the Draft SODAR Deployment Plan into the Final Detailed Measurement Program Plan.

Locations of Focus Areas

Task 2 of the Wind Energy Resource Modeling and Measurement Project identified five Focus Areas to be covered by the Measurement Program. These areas are referred to as:

- Antelope Valley Focus Area
- Mojave Desert Focus Area
- San Gorgonio Pass Focus Area
- Shasta Valley Focus Area
- Blue Ridge Focus Area

The centroids of the focus areas are listed in Table 1.

Group	Focus Area Name	Longitude	Latitude
B	Mojave Desert	-116.83155	35.03514
C	San Gorgonio Pass	-116.62582	33.93259
D	Antelope Valley	-118.30435	34.81656
H	Mayacamas Mountains	-122.66575?	38.69379
I	Shasta Valley	-122.44268	41.51182

Table 1

Measurement Locations

Measurements will be made from locations within the boundaries of all of the Focus Areas and from three or four tall towers within or near the Focus Areas. A SODAR unit will be used for Focus Areas that lack a representative tall tower. Each Focus Area will be instrumented with a SODAR unit. Some Focus Areas will be equipped with both an instrumented tall tower and a SODAR unit. This will allow further study of the Focus Area and comparison of the data generated by the two types of equipment.

The centroid of the Antelope Valley Focus Area is 25 km southwest of Mojave, California. In general, the terrain within this Focus Area is flat, sloping upwards on the northern, western, and southern edges. The City of Mojave, located in the northern portion of the Focus Area, has an elevation of 841 m. Lancaster, in the south of the Focus Area, is at 718 m. At the centroid, the prevailing wind direction is from the southwest. Temperatures range from highs of 44^{o}C to lows of –21 ^{o}C.

The centroid of the Mojave Focus Areas is located 26 km northeast of Barstow, California. It is composed of mixed terrain. In the south of the Area is the Mojave Valley. The Calico Mountains form the mid-section of the Focus Area. Flat regions intermixed with mountains extend north, away from the Calico Mountains. The Mojave Valley is roughly 550 m in elevation. The Calico Mountains peak at 1180 m. The floor of the flat northern area is roughly 1060m while the mountains there reach roughly 1300 m. At the centroid, the prevailing wind direction is from the west. Temperatures range from highs of 48 ^{o}C to lows of –13 ^{o}C.

The centroid of the San Gorgonio Pass Focus Area is located 15 km northwest of Palm Springs, California. The San Gorgonio Pass runs roughly east to west, transitioning from roughly 725 m in the west to 225 m in the east. At the centroid, the prevailing wind is from the west-southwest. Seasonal temperatures ranging from highs of 51 ^{o}C to lows of -12 ^{o}C.

The centroid of the Shasta Valley Focus Area is located 11 km northwest of Weed, California. The valley is marked by hills. The typical elevation of the valley floor is 250 m. To the south, mountains border the area. At the centroid, the prevailing wind direction is from the south-southeast. The climate varies, with temperatures ranging from typical highs of 39 ^{o}C to lows of –24 ^{o}C.

The Mayacamas Mountains Focus Area consists of a ridgeline that runs roughly north-west to south-east on the border of Sonoma and Lake Counties. Its centroid is located 28 km north-northeast of Santa Rosa, California. It includes Mount Saint Helena and ranges from a high point of 1435 m to a low of 95 m. At the centroid, the prevailing wind direction is from the northwest. Temperatures range from typical highs of 28 ^{o}C to lows of -6 ^{o}C.

Equipment Locations

A multi-level meteorological measurement system will be installed on three or four existing tall towers.

Location of the SODAR Units

Mojave Desert (Focus Area B)

One SODAR unit will be sited for three to four weeks, ideally in the northwest of the Focus Area in a relatively flat area with a class 5 wind resource. The majority of the area is controlled by the Bureau of Land Management (BLM).

San Gorgonio Pass (Focus Area C)

One SODAR until will be sited for three to four weeks in a class 5 to 7 wind resource area, out of the influence of active turbines. Currently, two sites are secured; both on the western end of the pass structure and well clear of active turbines. One of the secured sites is controlled by the BLM and the other is privately held.

Antelope Valley (Focus Area D)

Two SODAR units will be sited in or near Focus Area D. The first SODAR will be sited in a representative location within the heart of the Antelope Valley wind resource for three to four weeks. Numerous sites are being considered, all with online meteorological towers owned and operated by Oak Creek Energy Systems.

The other SODAR will be sited within the Oak Creek Energy Systems plant, located northwest of the Focus Area, for one to two weeks. The unit will be placed out of the influence of active turbines. The Oak Creek plant is home to the Oak Creek tall tower

Mayacamas Mountains (Focus Area H)

One SODAR unit will be sited for three to four weeks on the primary ridgeline within the northwest section of Focus Area D. The Geyserville tall tower is located on Geyser Peak, to the west of the planned SODAR site. The ridgeline is controlled by the BLM and private owners.

Shasta Valley (Focus Area I)

One SODAR unit will be sited for up to five weeks within the primary wind resource of the Shasta Valley. The selected location is the Shasta Airport, away from ground and air traffic. The airport is operated by the County of Siskiyou.

Montezuma Hills

One SODAR unit will be sited for one week in a class 3 or better wind resource, preferably as close as possible to the Dozier tall tower. The land is controlled by enXco, FPL, SMUD, and private landowners.

Two SODAR measurement systems (one leased from the supplier and one owned by TrueWind) will be used for the project. They will be set up at each measurement location for a minimum of 3 weeks. SODAR siting will follow standard conventions, including requisite standoff distances from obstructions, water bodies, ambient sounds, aircraft flight paths, and bird habitats. TrueWind employees will conduct setup and breakdown of the SODAR units.

Measurement Period

The tall tower instrumentation will gather equipment for 12 months after the equipment is commissioned.

SODAR deployments of three to four weeks aim to comprehensively characterize the wind resource at a site by collecting measurements over several synoptic weather cycles and tying the measurements to a long-term record. Such a characterization typically requires three weeks but can require additional weeks due to the variability of weather patterns and possible equipment downtime.

SODAR deployments of one to two weeks provide a snapshot of the wind resource. Such short campaigns are more effective when used in conjunction with a nearby meteorological record or additional SODAR deployments.

SODAR Deployment Schedule

The tentative schedule of SODAR operational dates in 2004 is listed below.

Leased Unit

Date Range	Location
4/07 – 5/11	Shasta Valley
5/13 – 6/08	San Gorgonio Pass
6/11– 7/07	Antelope Valley
7/09 – 7/16	Oak Creek Energy Systems

TrueWind Unit

Date Range	Location
6/05 – 6/30	Mayacamas Mountains
7/03 – 7/28	Mojave Desert
7/31-8/07	Montezuma Hills

Preparation and Installation of Equipment

TrueWind Solutions will specify and acquire the tall tower system components. The equipment will be programmed, tested, and packaged for shipment in-house before being sent to the field for installation. A tower climb contractor will complete tasks requiring scaling of the tower. The tower owner's climb contractor will be the preferred installation agent. The selection of a climb contractor will be dependent on rigger experience with similar work. A TrueWind employee will oversee the work of said contractor. TrueWind personnel will perform the tasks not requiring a tower climb contractor.

Vertical and horizontal separation of equipment mounted to tall towers will be consistent with the International Energy Association's specifications for the instrumentation of tall towers. For lattice towers, this means instruments are to be at least 3.75 times the tower face width away from the closest portion of the tower. In the vertical dimension, instruments are to be mounted at least 3 obstruction diameters from non-solid equipment mounted to the tower and 7 obstruction diameters from solid equipment on the tower. In addition, instruments are to be placed on a mast at least 10 times the height of the mounting boom. Finally, the instruments must be mounted at least 5 horizontal instrument-diameters away from any other instruments. Refer to Figure 1 for a pictorial representation of the International Energy Association's specifications. Different specifications apply to obstructions on the tower and non-lattice towers.

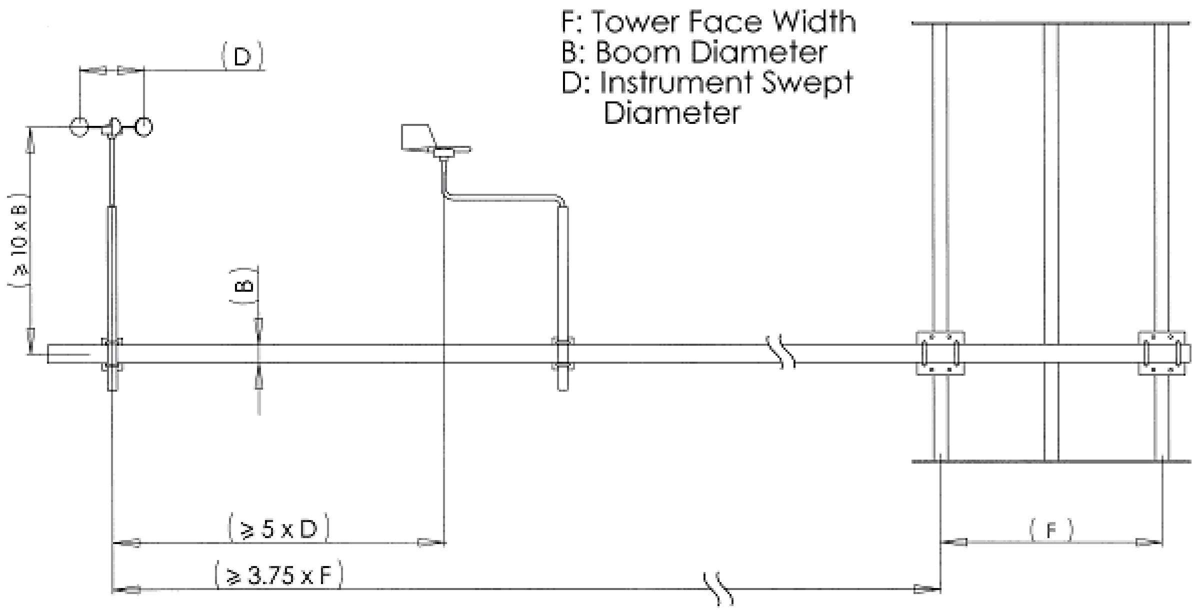

Figure 1

TrueWind owns one SODAR unit and will lease one unit for the measurement program. TrueWind will ensure that the SODAR units are properly specified, acquired, and configured for the measurement program. They will then be transported to the sites in California. The setup, testing, and breakdown of SODAR equipment will be carried-out by qualified TrueWind personnel.

Wind Speed Measurement

Wind speed will be measured at three heights on each tall tower. These heights will depend on the height and space availability of each tower but typical heights will be 50, 75, and 100 m. At each level there will be two anemometers in order to minimize instrument error, maximize reliability, and provide for data validation. Data validation will ensure that data from instrumentation in the wake of the tower will be discarded and replaced by data outside the wake of the tower. TrueWind plans to use the NRG Systems Max 40 Calibrated Cup Anemometer. Anemometers will be oriented into the direction of prevailing winds. If this is not possible or there is more than one prevailing direction, sensors will be mounted to minimize tower and instrumentation wake effects.

For the SODAR units, wind speed will be measured from 30 m to roughly 150 m at 10 m intervals. The maximum measurement height depends on site conditions such as humidity, ambient noise, and atmospheric stability.

Mounting Boom Design

Mounting booms will be used to hold the anemometers and wind vanes away from the tall towers. The use of appropriate booms minimizes the disturbance of airflow by the tower's presence in the flow stream.

Wind Direction

Wind direction will be measured at three heights on each tall tower. These heights will depend on the height and space availability of each tower but typical heights will be 50, 75, and 100 m. There will be one NRG Systems 200P wind vane mounted on each level. Wind direction sensor orientation will be verified in the field to properly reference true north.

For the SODAR units, wind direction will be measured for points starting at 30 m and extending to roughly 150 m, at 10 m intervals. The maximum measurement height depends on site conditions such as humidity, ambient noise, and atmospheric stability.

Air Temperature

Air temperature will be measured on each tall tower by two RM Young 41342 Temperature Sensors, each mounted in a six-plate radiation shield. The lower temperature sensor will be mounted at 10m. The height of the upper temperature sensor will depend on the height of the tower but the typical height will be 100 m. above the ground. The actual measurement height will be documented.

For the SODAR units, air temperature will not be recorded.

Irradiance

Solar radiation will be measured at each tall tower and SODAR by a LiCor Li-200SA pyranometer. Measurement will be made at a height of 1-3 m. The actual measurement height will be documented.

Precipitation

For the instrumented tall towers, precipitation will not be measured.

For the SODAR units, a rain gauge and/or precipitation sensor will be used to determine the existence of precipitation in order to assist in data validation.

Data Collection

Wind speed, wind direction, air temperature, and irradiance will be measured at a sampling rate of 0.5 Hz at each tall tower. A number of datalogger status parameters will also be recorded. The following parameters are archived into the logger every ten minutes:

- Average
- Standard deviation
- Minimum
- Maximum

For the SODAR units, wind speed and wind direction are measured at a sampling rate of 0.3 Hz. Irradiance and precipitation are measured at 1 Hz. Data quality and system status parameters are also recorded. The following parameters are archived into the logger every ten minutes:

- Average wind vector
- Average wind direction
- Mean of each of the three wind speed components
- Standard deviation of each of the three wind speed components
- Data quality parameters
- Average irradiance
- Various system status parameters

Data Acquisition System

For the instrumented tall towers, data will be stored on the datalogger.

For the SODAR units, data will be recorded on the unit's laptop computer.

Instrumentation Checkout and Field Calibration

The following tasks will be performed in the TrueWind office prior to the installation of the dataloggers used on instrumented tall towers:

- Datalogger programming and testing
- Communication system programming and testing
- Meteorological instrumentation testing

Once the equipment is installed at the site, a functionality check will be conducted for each sensor reading. All input data channels will be inspected to verify proper operation upon completion of the installation. Listed in Table 2 are the channel number, parameter name, sensor type, sensor location (assuming a typical upper instrumentation height of 100 m), sensor manufacturer, and sensor model for all sensors used per instrumented tall tower.

Ch.	Sensor Location	Parameter Name	Sensor Type	Sensor Mfg.	Sensor Model
1	100 m	100 m primary wind speed	cup anemometer	NRG	#40C
2	100 m	100 m redundant wind speed	cup anemometer	NRG	#40C
3	75 m	75 m primary wind speed	cup anemometer	NRG	#40C
4	75 m	75 m redundant wind speed	cup anemometer	NRG	#40C
5	50 m	50 m primary wind speed	cup anemometer	NRG	#40C
6	50 m	50 m redundant wind speed	cup anemometer	NRG	#40C
7	100 m	100 m wind direction	wind vane	NRG	#200P
8	75 m	75 m wind direction	wind vane	NRG	#200P
9	50 m	50 m wind direction	wind vane	NRG	#200P
10	1-3 m above ground	irradiance	pyranometer	Li-Cor	200SA
11	100 m	ambient temperature	temperature sensor mounted in radiation shield	RM Young	#41342
12	10 m	ambient temperature	temperature sensor mounted in radiation shield	RM Young	#41342

Table 2

The instrumentation checkout and field calibration procedures listed below are to be performed every six to eight weeks on each SODAR unit:

- Testing each speaker for proper transmission
- Testing the output of the speaker array every
- Occasional testing the response of the speaker array to incoming signals

Data Collection Procedure

TrueWind will remotely retrieve and validate the tall tower data on a weekly basis to ensure that the data acquisition system is functioning properly. In areas where sufficient cellular service exists, data will be transmitted using an NRG Systems Symphonie® iPack. In locations where cellular service is not suitable for data transfer, the data will report via a landline telephone service. If both options listed above are unavailable, regular site visits will be made to the datalogger to recover the data.

For the SODAR units, recorded data will be transmitted to TrueWind via a cellular phone on a daily basis. If cellular service is not available at the SODAR's location, a local representative will travel to the SODAR and retrieve the data on a weekly basis.

Data from the tall towers and SODAR units will be subject to rigorous quality control by TrueWind to identify any problems so that necessary repairs can be made quickly with minimal data loss.

Test Log Book

TrueWind will prepare a site log to record the relevant information about the meteorological equipment. It will note the following information for each site visit:

- Date and time of the site visit
- Meteorological conditions during the site visit
- Reason for the site visit
- Evidence of site tampering
- Information about the structural state of the tall tower or SODAR unit
- Record of instantaneous measurement values during the site visit
- State of the system during the site visit
- Contents of the error log during the site visit
- List of tasks performed at the site visit

Data Processing and Analysis

Raw data will be archived onto CD for backup once a week. Raw files will be imported into MS-Excel or MS-Access to develop a site database for each location.

The accuracy of measurements from the tall towers deteriorates during periods of icing. TrueWind plans to use ambient temperature and the standard deviation of wind direction as the primary method to detect icing events.

For the SODAR units, the accuracy of measurements deteriorates during periods of precipitation. TrueWind plans to use a rain gauge to detect precipitation. Also periods with a signal-to-noise ratio less than a threshold amount will be considered invalid. Finally, signal amplitude profiles will be examined to determine if fixed-echo effects may be compromising measurements.

Troubleshooting

TrueWind maintains a staff of engineers and specialists to diagnose and correct problems with the measurement equipment in a timely fashion. Problems will be detected during the setup process and via data processing and analysis.

IV

Final Boundary Layer Research and Findings Report

Draft Boundary Layer Research and Findings Report

Prepared For:

California Energy Commission
Contract No. 500-03-006

Prepared By:

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Classification
CLIENT'S DISCRETION

Review Standard
SENIOR STAFF

December 7, 2005

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DOCUMENT HISTORY

Issue	Date	Summary
A	December 7, 2005	Draft Report

Table of Contents

List of Figures

List of Tables

1.0 Identify Poorly Simulated Cases Associated with Boundary Layer Model Problems

The first step in this subtask was to identify the typical model biases and problems. The next step was to identify those problems that were likely related to the boundary layer. The final step was to identify the meteorological cases that were representative of a given boundary layer related problem in order to perform model experiments in an attempt to identify the source of and solutions to the problems.

Two approaches were used to help identify the model problems relevant to the boundary layer. One approach was an objective statistical analysis of the model output of many cases with observations from various sources to determine where the model was having problems simulating the boundary layer winds. The other approach was a subjective point comparison of model soundings with observed soundings for individual cases. The analysis involved comparing observed wind speed data from sodar, towers, rawinsonde and standard METAR observations with the model output.

The following were three categories of problems identified from the observations that were most likely related to boundary layer problems: (1) atmospheric stability related, (2) terrain complexity related, and (3) problems related to the surface energy budget formulation.

1.1 Problems Related to Atmospheric Stability

There were three model related problems identified that seemed to relate to atmospheric stability:

(a) A general high wind bias in the simulations within the first few hundred meters of the surface. Figure 1 shows a typical example of the low-level high wind speed bias of the model. This is most noticeable during the nighttime when the simulated winds near the surface are too high as noted in Figure 2. The high bias would seem to be related to the thermal structure and stability of the boundary layer during the nighttime hours and lack of model resolution. Figure 3 shows an idealized vertical profile of the wind and temperature that is typically associated with a nocturnal stable layer. Figure 4 gives the mean observation versus the mean model wind speed changes from 00 - 06 local. The sodar and tower measurement were particularly helpful in understanding the nature of the wind speed bias in the lower 200 meters.

(b) The simulated winds show too much vertical shear within the boundary layer when the atmosphere is stable. The sodar data was of great help helpful in identifying this problem. Figure 5 shows an idealized comparison of the model versus observed structure of the shear in the lower part of the boundary layer. Figure 6 shows a comparison of the sodar and model generated wind speeds.

(c) Difficulty in simulating winds transitioning from nocturnal to daytime boundary layer winds.

Problems related to atmospheric stability generally seem to be the result of the model not being able to resolve or properly handle the energy transfer within the boundary layer during periods when the boundary layer is stable. This problem is most noted during the late evening and early morning hours during periods of clear skies. The surface, rawinsonde, tower and sodar observations all indicate that during these stable periods, there is a tendency of the simulated winds to be higher than observed.

1.2 Problems Related to Terrain Complexity

Any atmospheric model will have difficulty simulating low-level airflow in complex terrain when important terrain variations are on the same scale or a smaller scale than the model's grid resolution. All of the active wind energy areas in California are in areas of complex terrain. Tower and sodar observations were used to help identify several terrain-related issues that involved horizontal resolution and non-hydrostatic forcing.

An example of the resolution problems can be seen in the San Gorgonio Pass area. The width of the San Gorgonio Pass is only a few kilometers, so a mesoscale model required grid spacing smaller than about 5 km to have a chance to fully resolve the relevant circulations of the Pass. Several experiments were performed to test the sensitivity of model results to the spacing of the finest nested grid. Figure 7 demonstrates the resolution issue that can result in either an over or underestimation of wind speeds in complex terrain.

Hydrostatic flow is one where the upward vertical pressure gradient force is balanced by the downward force of gravity. Typically mesoscale flow is largely hydrostatic, because we observe vertical accelerations to be much smaller than horizontal accelerations. In areas of steep terrain however, vertical accelerations may be large and a non-hydrostatic model may be essential. Experiments were performed to test whether the use of non-hydrostatic physics in the MASS model would improve the simulation of wind speeds in California. The general results indicated that there are two consequences of running hydrostatically in steep mountainous areas. The first is that model generated wind speeds tend to be a little high at the peak of the mountains (Figure 8) and the high wind bias will extend out into the plains for about 100 km during conditions of strong downslope conditions as shown in Figure 9.

Each mesoscale model handles terrain somewhat differently. In an attempt to determine if there is any significant sensitivity to the model formulation, different models were tested to see if they produced significantly different results in areas of complex terrain.

1.3 Problems Related to Surface Energy Budget Formulation

The surface, tower and sodar observations were used to identify two model-related problems that seem to be related to the surface energy budget. At times the model is unable to properly resolve or develop observed mesoscale circulations. This results in either missing, misplacing or mistiming the circulations. Figure 10 shows an idealization of the problem.

Proper formulation of the surface energy budget is critical to simulating the boundary winds correctly. There are several components to the surface energy budget. First, there is the short and long wave radiation physics that must be handled correctly. Second, there is the soil dynamics and hydrology including evaporation and transpiration. Finally, there is the input data for components such as surface roughness, soil type, and soil moisture that play a critical role in the surface energy budget. If any of these components of the surface energy budget are not modeled correctly, mesoscale circulations that are driven by thermal differences will not be properly simulated.

1.4 Summary of Problems

To consistently simulate the winds correctly within the boundary layer in very complex terrain areas such as California, the model must handle the stability, terrain and surface energy budget correctly. However, it is useful to divide the problems into three categories: (1) stability, (2) terrain and (3) surface energy budget because there seems to be situations where one of the problems dominates the other two.

2.0 Results of Model Experiments

A series of model experiments were conducted in an attempt to find the actual cause of the noted problems and to find solutions if possible.

2.1 Atmospheric Stability Experiments

The following experiments were performed in an attempt to find better ways to handle the stable boundary layer.

(1) Resolution experiments

(2) Boundary layer stability regimes experiments

(3) Boundary layer formulation experiments

2.1.1 Results from Resolution Experiments

Simulations were made with a horizontal grid spacing 30 km, 8 km, and 2 km. The results did show some improvement with higher resolutions, however, it may take a resolution higher than 1 km to fully resolve the boundary layer. One result of increasing the model resolution is to increase the relative impact of friction because of the smaller grid cells. Thus, there is a natural tendency to lower the near-surface wind speeds as model resolution is increased.

Table 1: Comparison of the performance of the models ability to produce accurate 50 m mean wind speed information based upon the horizontal grid resolution.

Location	Observed Speed	Modeled Speed		
		30 km Resolution	8 km Resolution	2 km Resolution
San Gorgonio	5.2 m/s	7.3 m/s	7.1 m/s	6.5 m/s
Mayacamas	6.9 m/s	8.5 m/s	7.6 m/s	7.4 m/s
Shasta	7.8 m/s	9.6 m/s	8.8 m/s	8.2 m/s

2.1.2 Results from PBL Stability Regime Experiments

Various sites were examined in order to examine the performance of the model based upon which of three stability regimes were activated: **stable**, **damped mechanical turbulence** and **forced convection**. A comparison of the absolute value of the difference between the modeled speeds versus observed speeds (model minus observation) was made for the PBL stability regimes for 730 hours of output. The results showed that there was a significantly larger mean wind speed error for the stable regime as compared to the unstable regimes. This further reinforces the idea that the problem with the high wind speed bias is associated with the stable boundary layer conditions.

Table 2: Comparison of the performance of model based upon the activated stability regime.

Stability Regime	Observed Speed	Modeled Speed	Mean Speed Error	Mean Direction Error
Stable regime	5.2 m/s	7.3 m/s	2.1 m/s	71.5 deg
Damped mechanical turbulence	6.9 m/s	8.5 m/s	1.6 m/s	83.9 deg
Forced Convection	7.8 m/s	9.6 m/s	1.8 m/s	68.2 deg

2.1.3 Boundary Layer Formulation Factors

As noted, observations from meteorological towers and sodar in various locations have shown that the MASS model tends to predict wind speeds that are systematically too high in the lowest 100 meters above the ground. Other research that has been done for various locations outside of California, have noted this same problem. This current and past research has also revealed that nearly all of the high bias occurs during the nighttime hours. An example of this problem occurred for a set of October 1999 30 km MASS simulations. When compared to observations at an instrumented tower near Wichita, KS (part of the CASES-99 project), MASS showed a positive bias of 1.1 m/s at 55 m above ground level, about 15% above the observed wind speed.

It was hypothesized that this high wind speed bias results from the inability of a traditional PBL scheme to correctly represent the mixing below nocturnal low-level jets. A traditional PBL scheme assumes that mixing is surface-based, missing the shear-driven turbulence at the top of the boundary layer. In contrast, at night, an "upside-down boundary layer" below the jet maximum is created, which sometimes penetrates downward into the shallow, stable nocturnal boundary layer.

A series of papers by Mahrt and collaborators (Ha and Mahrt 2001; Mahrt and Vickers 2005) proposed a planetary boundary layer formulation that is independent of a z (vertical) coordinate ("z-less"). In this formulation, mixing can be parameterized as a function of local shear and stability that is unrelated to the state of the surface-based boundary layer, and thus could improve upon the traditional approach. A portion of the Mahrt and Vickers (2005) scheme was merged into the MASS Turbulence Kinetic Energy (TKE) scheme. The essential change is that an additional mixing length is calculated which depends entirely on local values of vertical stability and wind shear (it is therefore independent of the z coordinate or "z-less"). If this local mixing length is greater than the original mixing length (which is a function of height within the boundary layer), then the local value is used, resulting in increased mixing. This can help to correct situations where the model often tends to under predict mixing, as in the common case of a nocturnal low-level jet developing above a shallow stable boundary layer.

The z-less scheme was tested in a California simulation and it produced a modest decrease in low-level wind speeds during the nighttime hours. Figure 11 shows the differences in 50 m wind speed caused by use of the z-less scheme over a 24 hr simulation on an 8 km grid beginning at 1200 UTC (0500 PDT) 15 July 2002. The wind speed decreases about 0.15 m/s at the beginning of the simulation under stable nighttime conditions, changes very little during the day, and then decreases again as the next night begins. Figure 12 shows spatial differences at 0600 UTC 16 July (2300 PDT 15 July); it can be seen that the z-less scheme reduces the wind speed in most areas in California by less than 0.5 m/s, although there are locations where the decreases are larger than 1 m/s. Some of the larger decreases appear to be in significant wind energy areas such as the Altamont Pass and the Tehachapi Pass. Figure 13 shows a profile of the wind speed differences created by the z-less scheme over a three month set (March-May 2005) of California simulations (all times of day averaged together). It is believed that these changes due to the use of the z-less scheme occur at the correct time of day and at the correct vertical levels, but the magnitude of the change only partially corrects the general low-level wind speed bias. Further "tweaking" of the scheme may correct more of the problem, or another part of the scheme may need additional attention.

2.2 Terrain Complexity Experiments

The following experiments were performed in an effort to find better ways to simulate the winds in complex terrain areas:

(1) Non-hydrostatic versus hydrostatic experiments

(2) Resolution experiments

(3) Sensitivity to mesoscale model

2.2.1 Non-hydrostatic versus Hydrostatic Experiments

To save computational resources, it can be reasonably assumed that there is a vertical balance between the pressure gradient force that is directed upwards and the force of gravity that is directed downwards. This assumption of balance is called the hydrostatic assumption. For relatively large areas (5 km grid spacing or larger) this assumption is very reasonable. However, for systems with strong forcing over small distances, such as thunderstorms and steep drainage winds, this assumption is not a good one because the vertical forces will not remain balanced and stronger vertical accelerations will occur, at least for short time periods. A variety of model experiments were performed comparing both the hydrostatic and non-hydrostatic versions of MASS with tower, sodar and surface observations in an attempt to examine the importance of non-hydrostatic forcing on wind climate.

Using the MASS Model over the San Gorgonio Pass in Southern California, simulations were made with a configuration of 30 km, 8 km, 2 km and 1 km hydrostatic, and 2 km and 1 km non-hydrostatic simulations. This allowed us to test both the sensitivity to resolution and running non-hydrostatically. The results of these experiments showed very little sensitivity to running non-hydrostatically. There are likely cases where the non-hydrostatic MASS does a better job, especially for extreme down slope conditions. But in most cases there is very little difference between the hydrostatic and non-hydrostatic wind speeds. The number of times there is a significant difference would not be significant when creating a long-term climatology of the wind speeds. Below are some specifics on each set of experiments.

2.2.1.1 Resolution

In order to examine the impact of running non-hydrostatically, resolution experiments were first run hydrostatically using 8 km, 4 km, 2 km and 1 km grid spacing. By comparing the model output to the tower, sodar and surface observations, we found that model resolution had a major impact on the quality of the simulations. In general, the simulations were not very representative until the resolution reached 2 km. The 1 km hydrostatic run did a little better than 2 km. The San Gorgonio Pass is quite narrow, so it seems clear that a grid resolution of less than 8 km and preferably 2 km or less is necessary to resolve it properly.

2.2.1.2 Hydrostatic versus Non-hydrostatic

In theory, we should see some improvement in the results when running non-hydrostatically. But there was very little difference; in fact, at 2 km grid spacing non-hydrostatic runs produced a slightly poorer comparison with observations than a corresponding 2 km hydrostatic run. The conclusion is that running non-hydrostatically is not a major factor for improving wind maps. It is likely that the non-hydrostatic forcing is relatively important for specific situations such as extreme Santa Ana conditions. Since we wanted to improve the climate statistics for wind, we were not looking for cases with extreme wind event problems. The cases we used were more typical of ones that give the model problems on a day-to-day basis. So these cases are not ones where non-hydrostatic forcing is significant.

Table 3: Comparison of the mean wind speed of model when in hydrostatic and non-hydrostatic mode.

Model Mode	Observed Speed	Modeled Speed			
		8 km Resolution	4 km Resolution	2 km Resolution	1 km Resolution
Hydrostatic	5.2 m/s	7.2 m/s	6.8 m/s	6.1 m/s	6.2 m/s
Non-Hydrostatic	5.2 m/s	7.2 m/s	6.7 m/s	5.9 m/s	5.8 m/s

2.2.2 Sensitivity to Mesoscale Model

In addition to the resolution experiments, experiments were run comparing two other mesoscale models with MASS to the tower, sodar and surface observations to see if the other models could handle the complex terrain and other problems better. The models used were (1) OMEGA, which is unique in that it uses an adaptive grid that can in theory resolve complex terrain areas more accurately, and (2) WRF, which is the new community mesoscale model being developed at the National Centers for Atmospheric Research.

2.2.2.1 OMEGA Results

A large OMEGA grid was set up over approximately the same region as the MASS grid that had been used to produce the output for San Gorgonio Pass. The size of the grid cells ranged from 35 to 70 km on the outer part of the grid, decreasing to 4 km in the vicinity of San Gorgonio Pass at the center of the grid.

On the encouraging side, the OMEGA run has westerly winds through the San Gorgonio Pass for the entire simulation that matched well with the observations. On the negative side, the wind speeds were lower than observed and some aspects of the OMEGA simulation did not appear to be realistic. The temperatures seemed too cool on the eastern side of the Pass, and the skin temperature varied greatly between adjacent cells.

The other major negative was the speed of the simulation when using OMEGA. MASS ran the 24-hour simulation for the domain in 18 hours, but OMEGA on the same machine took 87 hours to complete. Even though OMEGA demonstrated some hope of producing superior results, given the slowness of OMEGA, we have not spent time to investigate the further use of OMEGA.

2.2.2.2 WRF Results

A large WRF grid was set up over approximately the same region as the MASS grid that had been used to produce the output for San Gorgonio Pass. The grid spacing for WRF was 4 km; identical to the OMEGA and MASS simulations.

A comparison of the output from the WRF with standard soundings, tower and sodar data revealed the following. The MASS and WRF 4 km results are strikingly similar in this complex terrain region. Both show westerly flow through the Pass for the first part of the day, a reversal to easterly for a few hours in the afternoon, then a resumption of westerly flow. The low-level temperature fields on the eastern side of the Pass appear to be similar for the two models, and both seem to be several degrees cooler than observed temperatures in Palm Springs and Thermal.

Observations, MASS and WRF each showed a mean sea level pressure gradient across the Pass (Riverside to Thermal), with higher pressure all day on the western side. But the pressures on the eastern side seem to be higher in MASS than WRF, with the pressure at Thermal rising to within 2 mb of Riverside late in the day. Observations show a 5-6 mb difference between Riverside and Thermal all day.

Table 4: Comparison of the mean wind speed of model produced by MASS, WRF and OMEGA.

Level	Observed Speed	Modeled Speed		
		MASS	OMEGA km	WRF
10 m	5.2 m/s	6.8 m/s	6.1 m/s	7.2 m/s
50 m	5.2 m/s	6.7 m/s	5.9 m/s	7.2 m/s

2.3 Surface Energy Budget Formulation Experiments

The following experiments were performed in an attempt to find better ways to simulate the winds in complex terrain areas:

(1) Non-hydrostatic versus hydrostatic experiments

(2) Resolution experiments

(3) Sensitivity to mesoscale model and surface energy budget formulation

(4) Sensitivity to input data surface and atmospheric data

2.3.1 Non-hydrostatic versus Hydrostatic experiments and Resolution Experiments

Resolution experiments investigating the surface energy budget problems revealed that neither resolution nor non-hydrostatic forcing were primary factors. For example, the reversal of wind flow appears in all of the MASS and WRF simulations for the Tehachapi locations (Oak Creek and Rosamond) regardless of the grid spacing or running non-hydrostatically. The wind reversal in the simulations does not show up in the observations.

2.3.2 Sensitivity to mesoscale model and surface energy budget formulation

A comparison of the surface energy budget generated by the WRF was made with the surface energy budget generated by MASS. We looked at the various upward and downward radiation fluxes to try to gain a better understanding of how the formulation of the radiation scheme as part of the boundary layer energy budget impacts the simulation of wind features in steep, complex terrain associated with the California passes. The net result of the study is that MASS and WRF energy schemes are very similar and produce similar results.

2.3.3 Sensitivity to Atmospheric Input Data

2.3.3.1 Atmospheric Data Sensitivity

The model experiment showed there was some sensitivity to the atmospheric input data. The atmospheric data that is ingested by the model comes in two forms: (1) gridded and (2) point observations. There was slight sensitivity to the gridded data source and there was significant sensitivity to the availability or non-availability of the point data. The following model experiments were run for the San Gorgonio 11 June 2002 case during March using MASS with a cold start:

1. 2 km hydrostatic 125x125x25, AVN gridded data only
2. 2 km hydrostatic 125x125x25, AVN, rawinsonde and surface,
3. 2 km hydrostatic 125x125x25, Eta, rawinsonde and surface
4. 1 km hydrostatic 125x125x35, AVN, rawinsonde and surface
5. 2 km non-hydrostatic 125x125x35, AVN, rawinsonde and surface,
6. 2 km hydrostatic 125x125x25, AVN, rawinsonde and surface, 24-hr spin-up

2.3.3.2 Source of Initial/BC Conditions

The runs using Eta (NAM) gridded data produced slightly better simulation results than the simulation that used data from the AVN (GFS) model.

2.3.3.3 Availability or Non-Availability of Observational Point

There was significant improvement in the accuracy of the output for those simulations that used both rawinsonde and surface data as part of the initial conditions.

2.3.3.4 Spin-up Time

When the beginning of the run was moved back 24 hours to allow more "spin-up" time, the San Gorgonio wind speed forecast improved somewhat.

2.3.4 Sensitivity to Surface Input Data

2.3.4.1 Soil Moisture

As the research progressed, it became apparent that the irrigation in the Coachella Valley (Palm Springs down to the Salton Sea) is a key factor in the simulated wind direction reversal problem in the simulations for the Tehachapi locations (Oak Creek and Rosamond). It seems that the irrigation significantly increases the soil moisture and causes a localized thermal and pressure gradient that reduces the up-valley daytime flow. Experiments with MASS, using modified surface moisture data, strongly indicate that the increase in soil moisture resulting from inferred irrigation can produce what is called "an inland sea breeze effect", which can significantly modify the direction of the surface winds. Because the irrigation information is not part of the typical input data in either the MASS or WRF, the simulated up-valley flow is much stronger than the observed up-valley flow. Figure 14 shows the improvement made to the wind direction simulation when the irrigation information is added into the soil database.

2.3.4.2 Sea Surface Temperatures

During the course of this research, as well as research for other projects, it became apparent that the sea surface temperature (SST) distribution can have a significant impact on the winds in California. It also became apparent that the SST database should include information on inland lake surface temperatures. The MASS model previously used one of two sources for the initialization of sea surface temperature: (1) A global database of monthly climatological SST at 0.2 deg (about 20 km) resolution; or (2) an NCEP global database of historical SST at 1 deg (about 110 km) resolution covering 1981 to the present at weekly intervals. We have found that both of these datasets have significant problems. The 1 deg historical data is extremely coarse, and even the 0.2 deg climatological data is too coarse to properly resolve important gradients of SST's in inland lakes and coastal oceans. The result is that the water surface temperature for lakes as large as the Salton Sea in Southern California are poorly known and the model may make an assumption which differs significantly from reality.

After searching for better, higher-resolution sources of SST data, we evaluated two different types of satellite-derived data from NASA: (1) AVHRR Pathfinder global data at 4 km resolution, which is available from the mid-1980's to the present; and (2) Aqua MODIS global data at 4 km resolution, which is available from July 2002 to the present. The use of these high-resolution datasets improve the SST fields in California runs, especially close to the coast and in places such as San Francisco Bay and the Salton Sea. The results have been more accurate simulations.

Figure 15 gives an example of the difference in temperatures using the courser data as compared with the higher resolution SST data. Figure 16 shows the improvements made in the wind speed when using the improved SST data.

3.0 Conclusions

The availability of the tower and sodar data enabled model versus observation comparison possible that lead to the identification of several model problems. The data also helped us determine the cause, and in some cases, the solution to the various problems.

The following are the key conclusions drawn from this research:

1. Model resolution is important in improving results for the stable boundary layer and in complex terrain regions. It is not important in resolving the surface energy budget problems.

2. The "z-less" boundary scheme improved the result for the stable layer cases.

3. Running non-hydrostatically may not make a significant difference when producing climate statistics for most areas.

4. There was little difference between the performance of MASS and WRF in terms of quality and timing. OMEGA did somewhat better in some aspects but is much slower to run than either WRF or MASS.

5. WRF PBL and radiative scheme comparisons with MASS results show that the schemes are quite similar in formulation and performance.

6. The use of higher resolution gridded data (ETA) for initial and lateral boundary conditions improved the results slightly.

7. The inclusion of point surface and rawinsonde observations as part of the initial conditions substantially improved the quality of the simulations.

8. Changes in soil moisture content made a difference in simulation. When the soil moisture was corrected to more accurately reflect irrigation patterns, the result of the test cases improved.

9. Sea surface temperatures have an effect on the winds in California. The more accurate the input data, the more accurate the results from the simulations.

Appendix

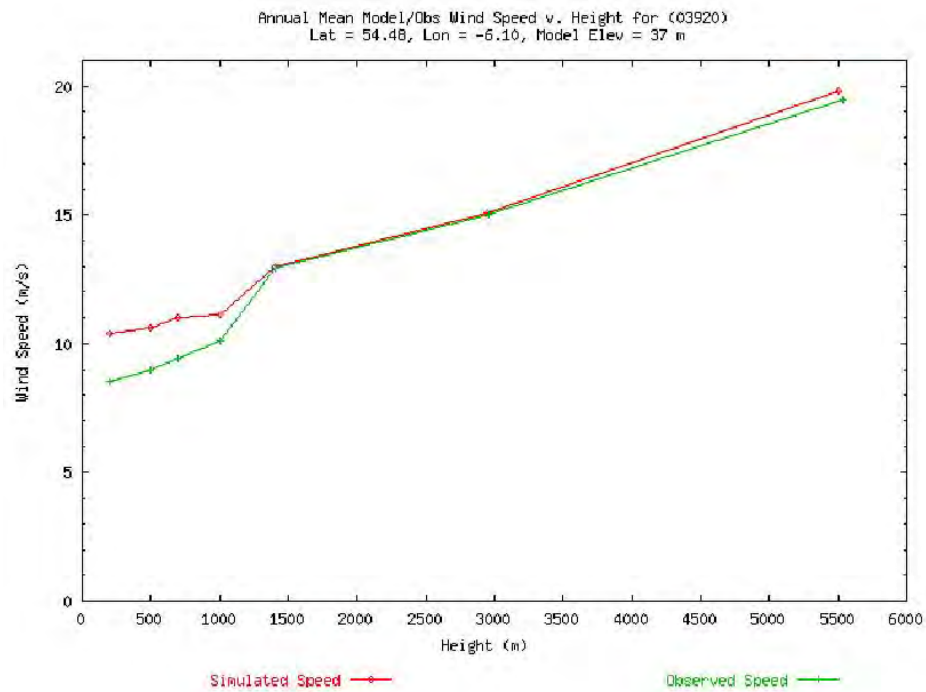


Figure 1: Example of observed versus model results, demonstrating high wind model bias

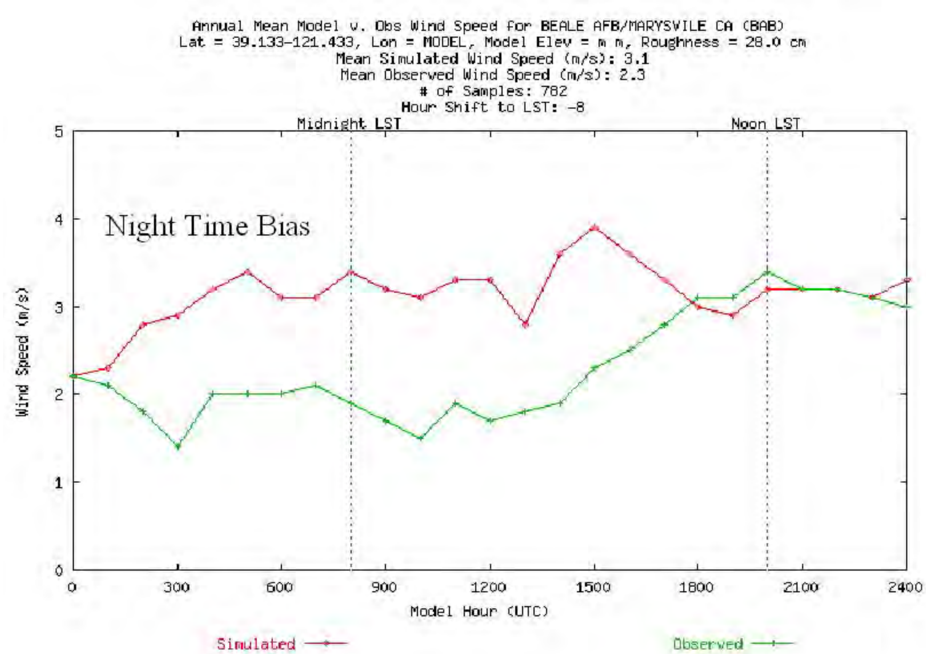


Figure 2: Example of the primarily nocturnal model wind speed bias

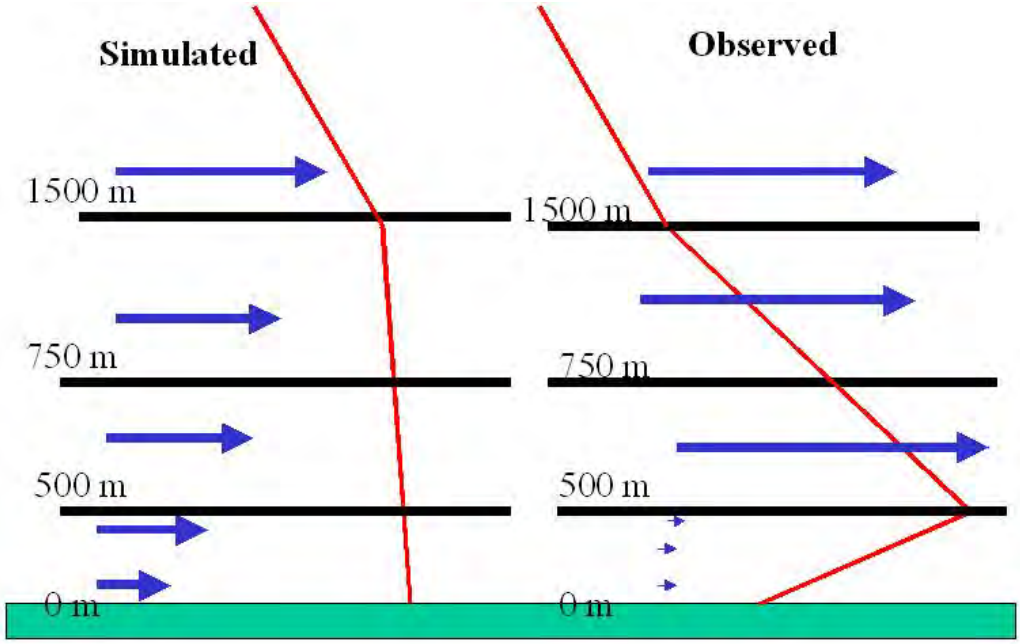


Figure 3: Over estimation of wind speeds near the surface due to coarse model resolution

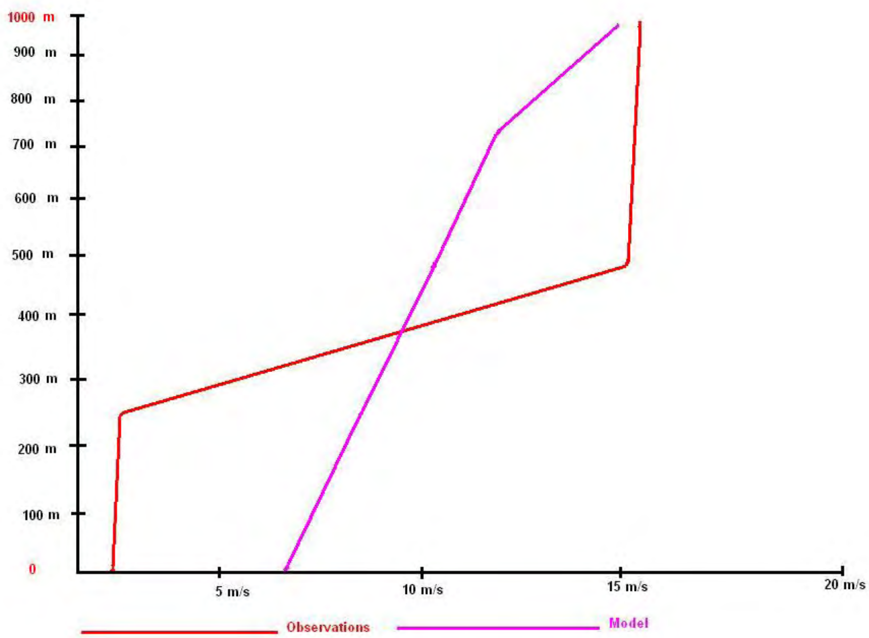


Figure 4: Observed and modeled wind speed changes from 00 - 06 local Time

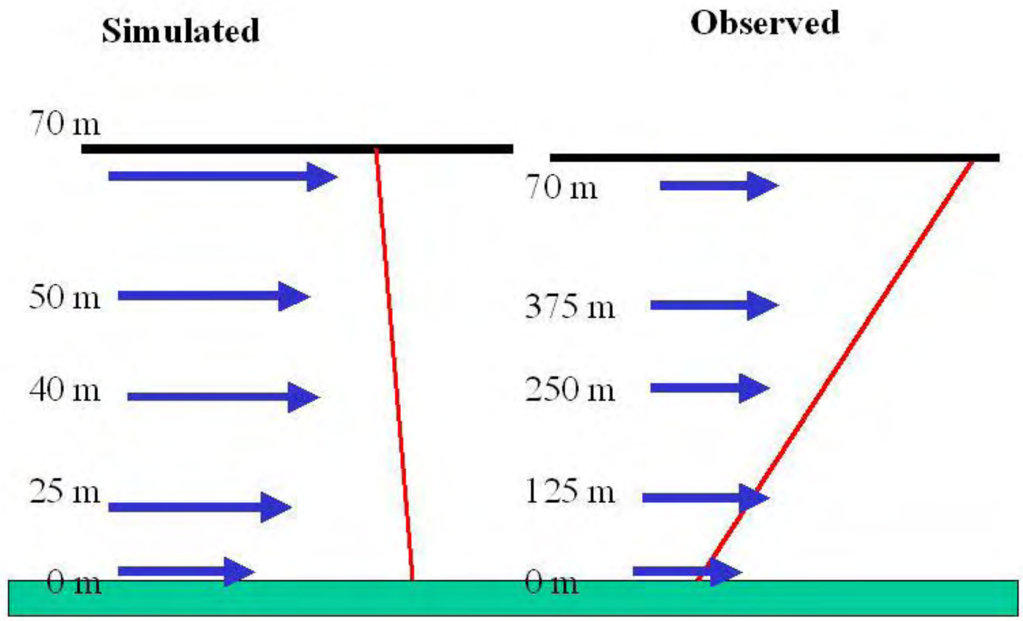


Figure 5: Over estimation of windshear near the surface due during in a stable boundary layer due to limited model resolution

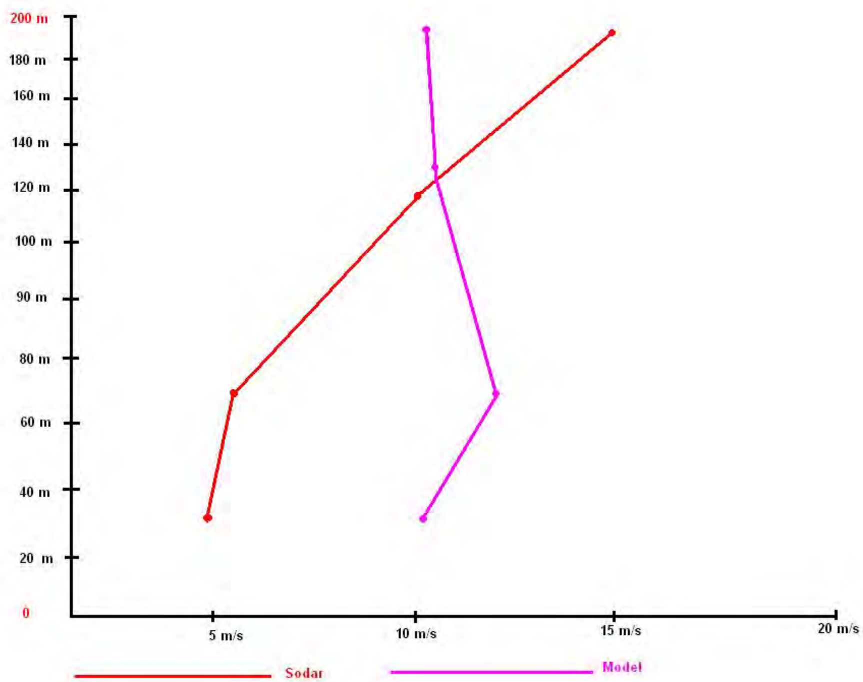


Figure 6: Observed sodar and model speeds from 00 - 06 local time.

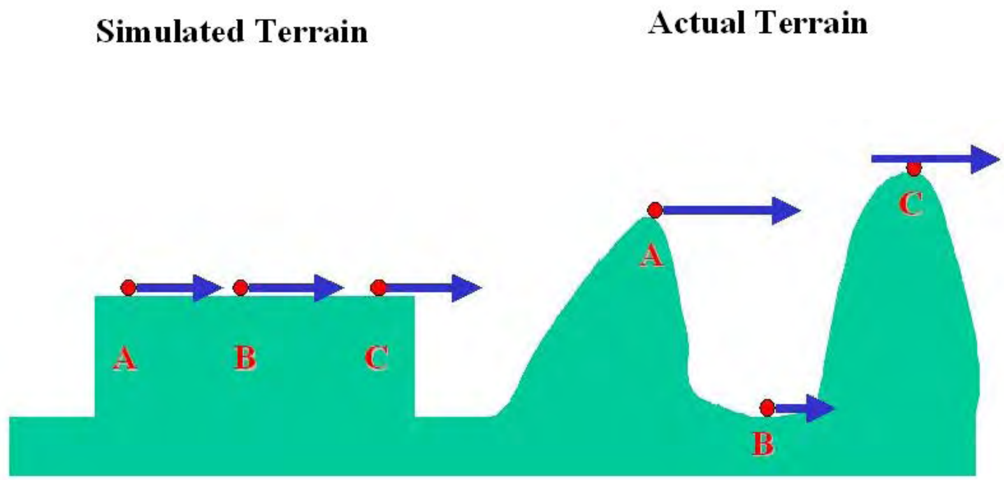


Figure 7: Result of limited model resolution in complex terrain, producing an over estimation of the winds at elevations higher than the model (A and C) and a lower estimation at elevations lower than the model (B)

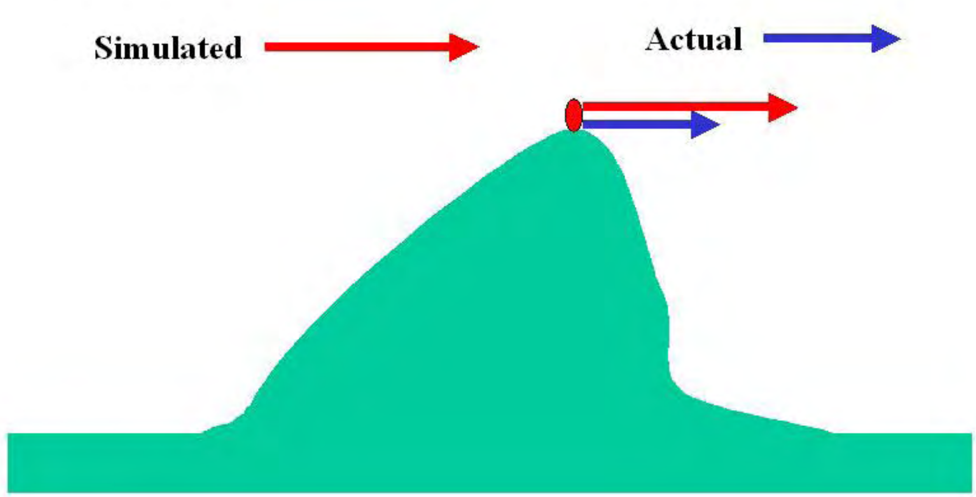


Figure 8: Example of overestimation of wind speeds at mountaintop using a hydrostatic model

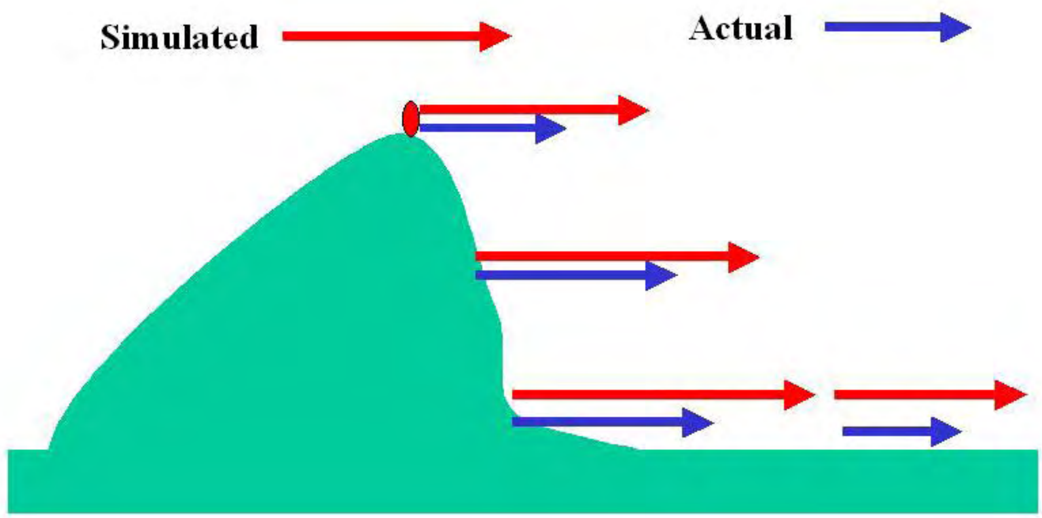


Figure 9: Example of overestimation of downslope flow with a hydrostatic model

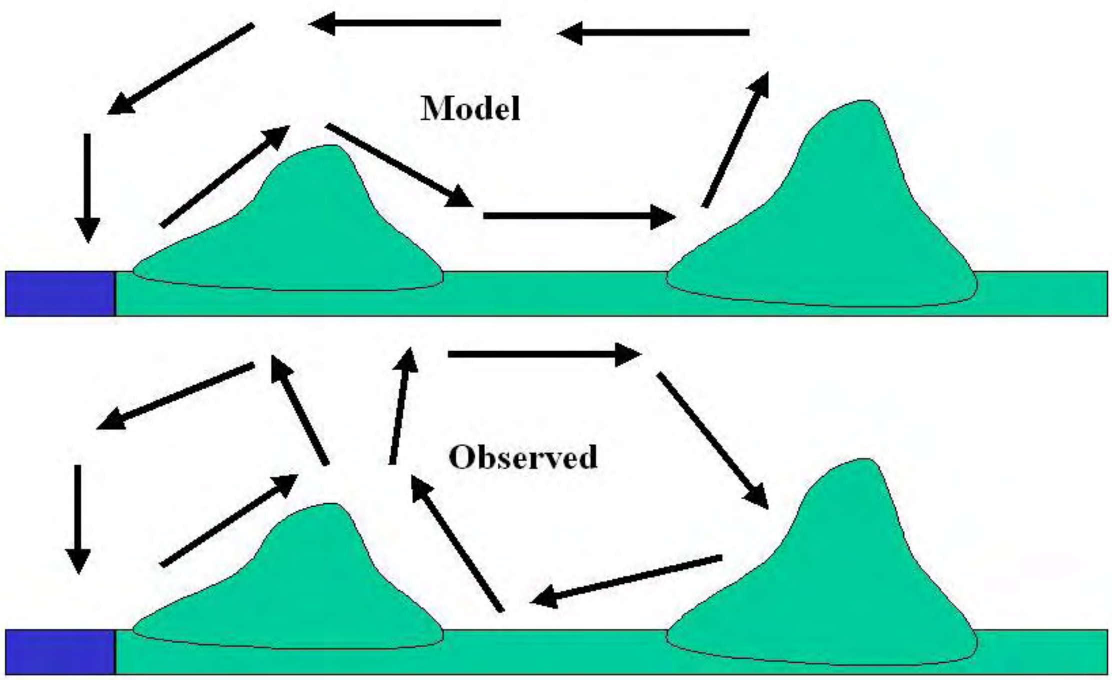


Figure 10: Errors in surface energy budgeting can lead to a poorly resolved or timed mesoscale circulations

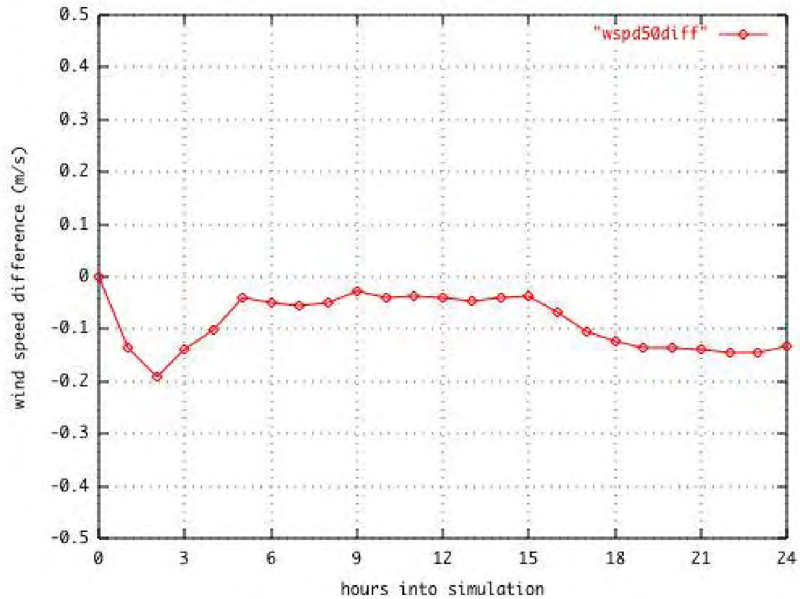


Figure 11: Comparison of 50 m modeled wind speeds using the traditional and z-less scheme, for an 8 km grid

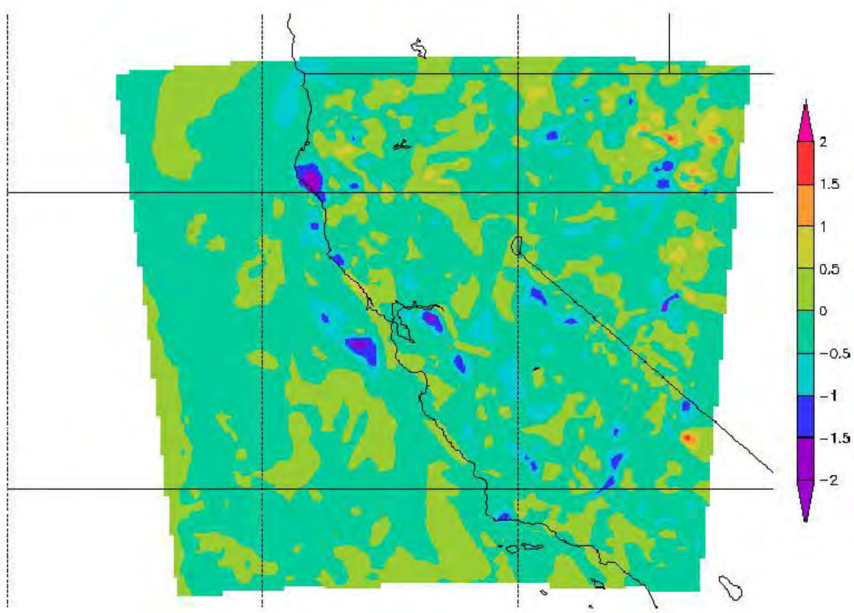


Figure 12: Spatial speed differences at 2300 PDT 15 July.
The z-less scheme reduces the wind speed in most areas in California by less than 0.5 m/s, although there are locations where the decreases are larger than 1 m/s.

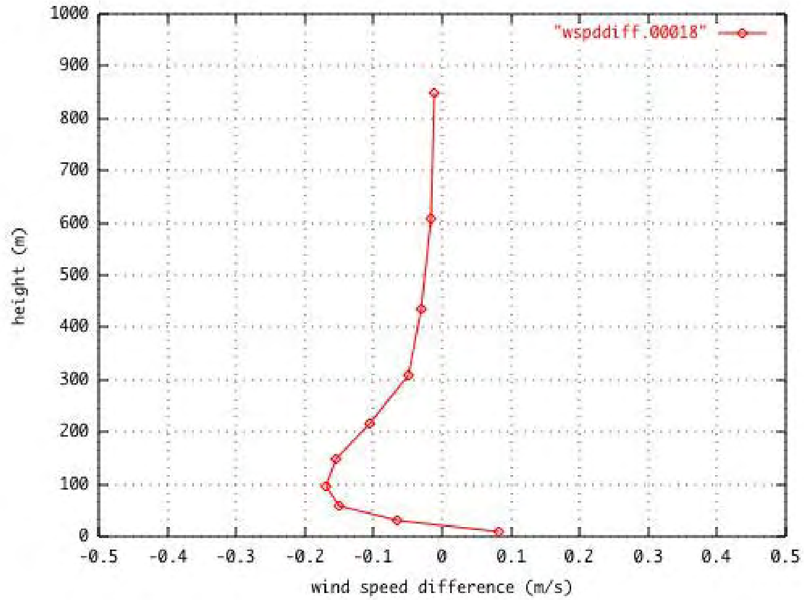


Figure 13: Profile of wind speed differences using the z-less scheme, for a three-month period (March-May 2005)

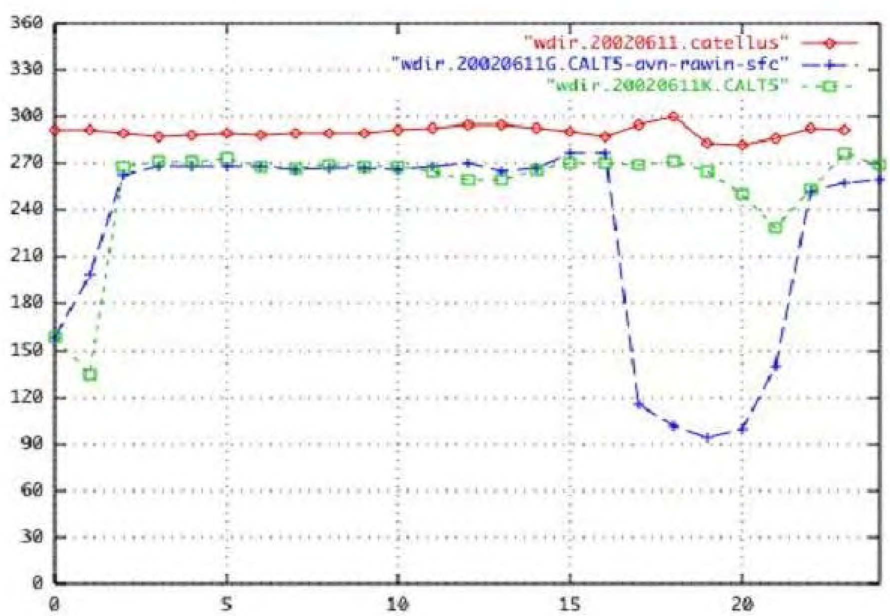


Figure 14: Comparison of the observed (red line) and modeled wind direction (green and blue lines).
The green line incorporates additional irrigation information in the soil database.

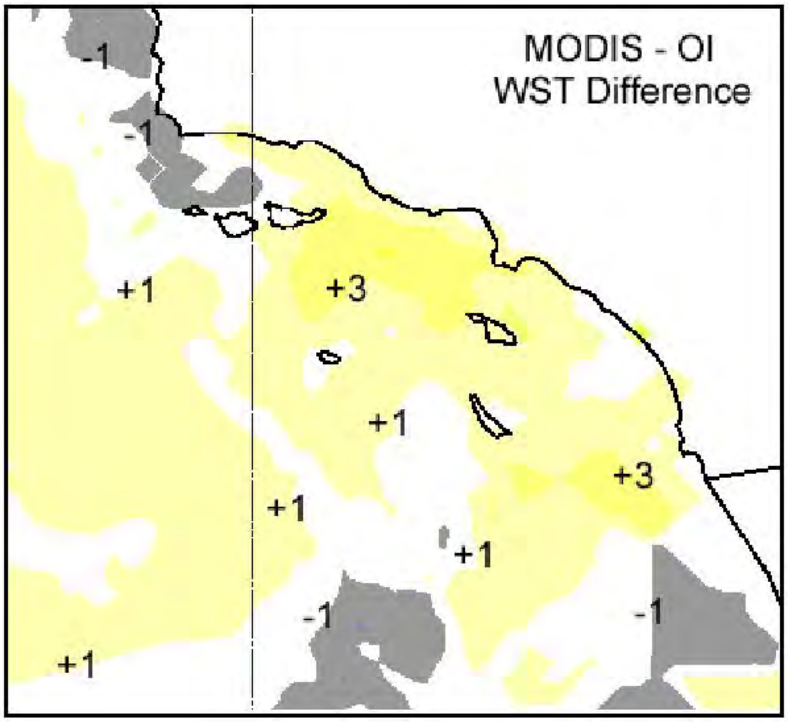


Figure 15: Differences in the initial skin temperature (degrees F) between the NCEP OI and MODIS WST for the 23 August 2002 forecast simulation

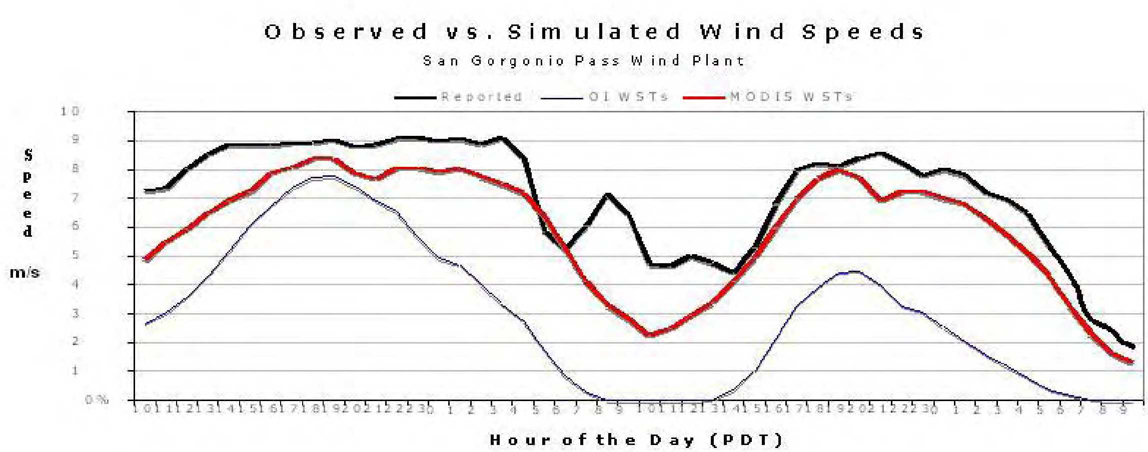
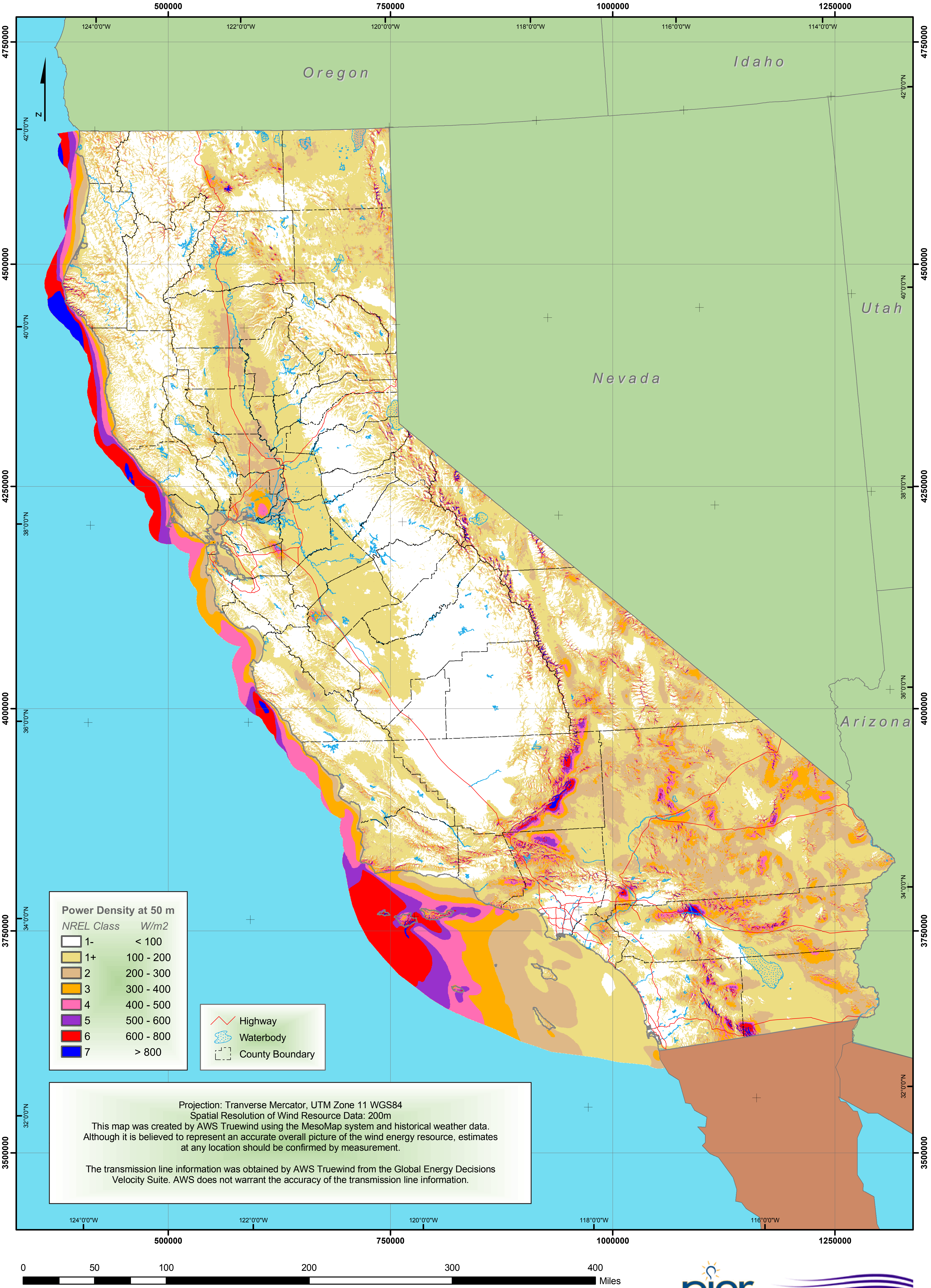


Figure 16: Simulated and observed wind speeds for the Mountain View wind plant for the period beginning at 9 AM PDT 23 August 2002

V

Final Statewide Wind Maps and Modifications Report

Wind Power Density of California at 50 Meters



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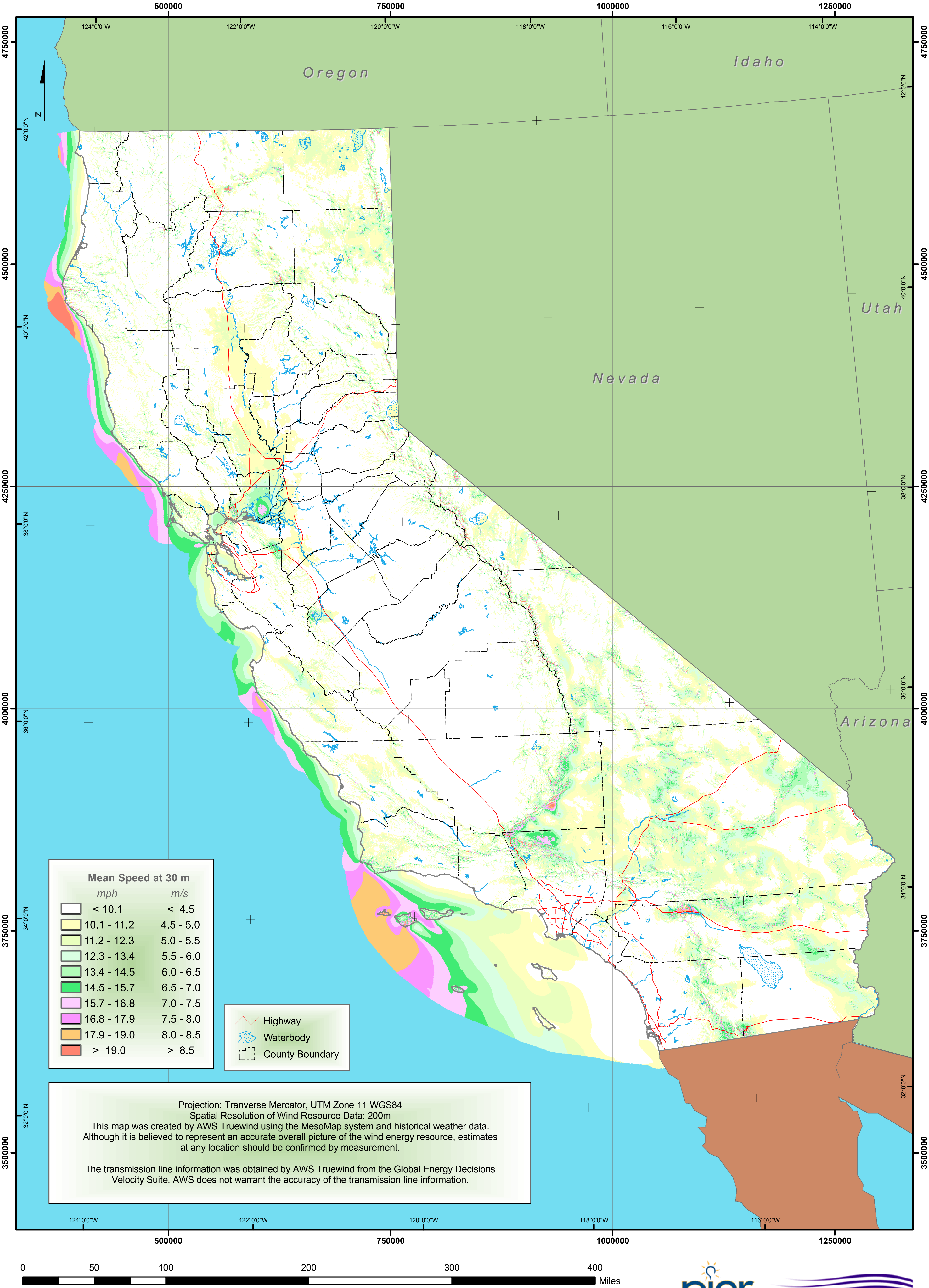
AWS Truewind LLC, 5/9/06

Mean Annual Wind Speed of California at 30 Meters



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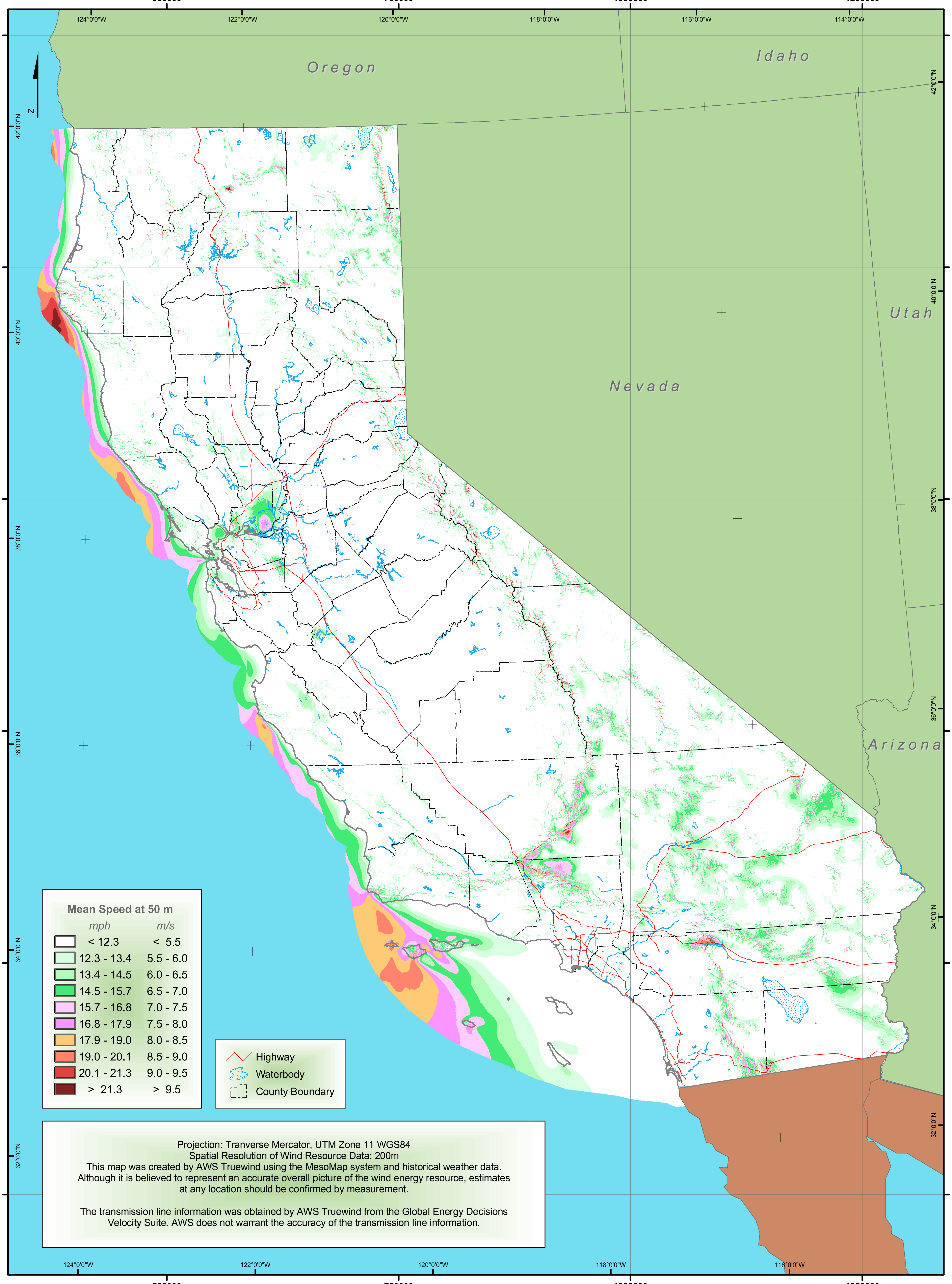
AWS Truewind LLC, 5/9/06

Mean Annual Wind Speed of California at 50 Meters



0 50 100 200 300 400 Miles

0 50 100 200 300 400 Kilometers

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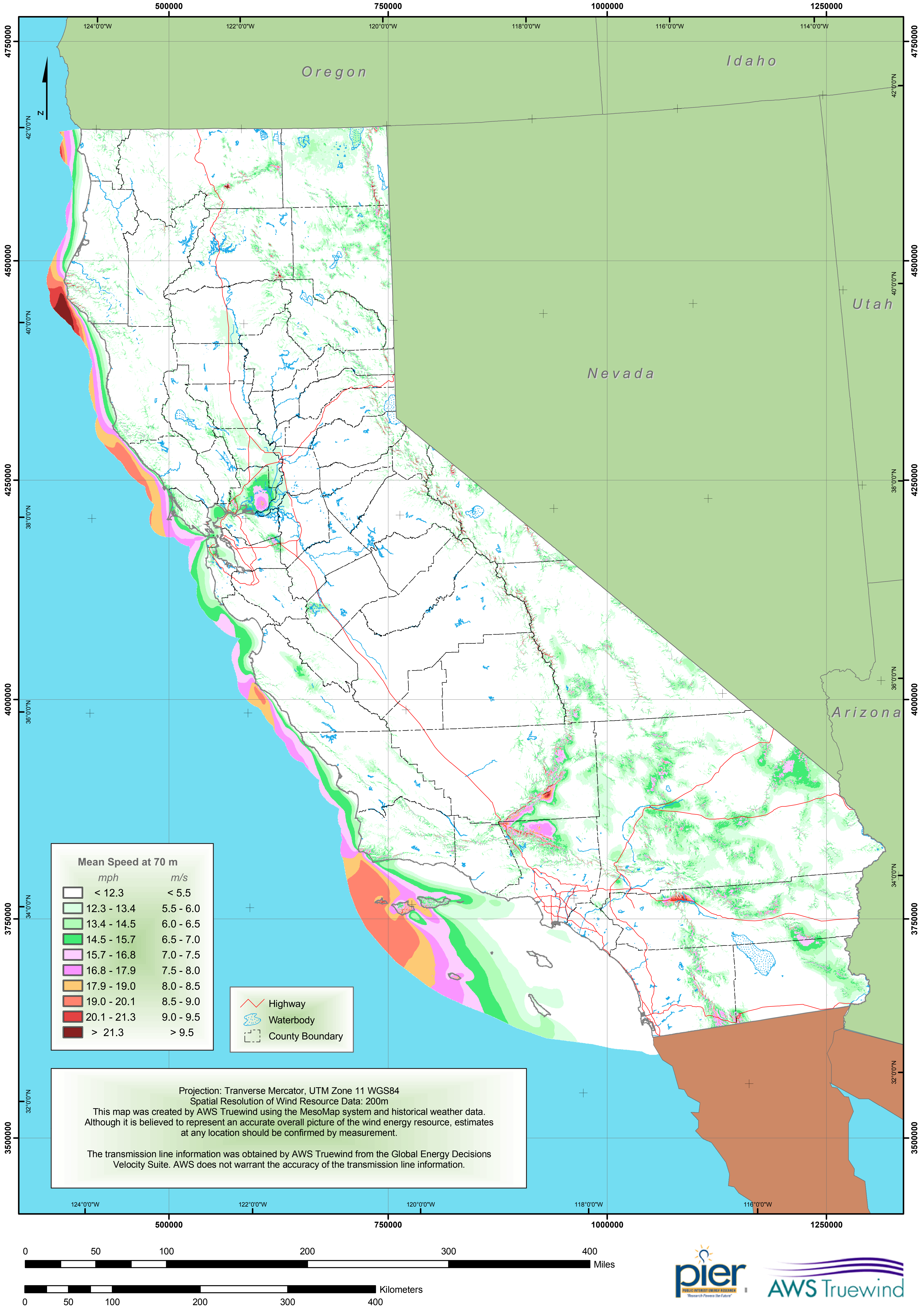
AWS Truewind

Mean Annual Wind Speed of California at 70 Meters



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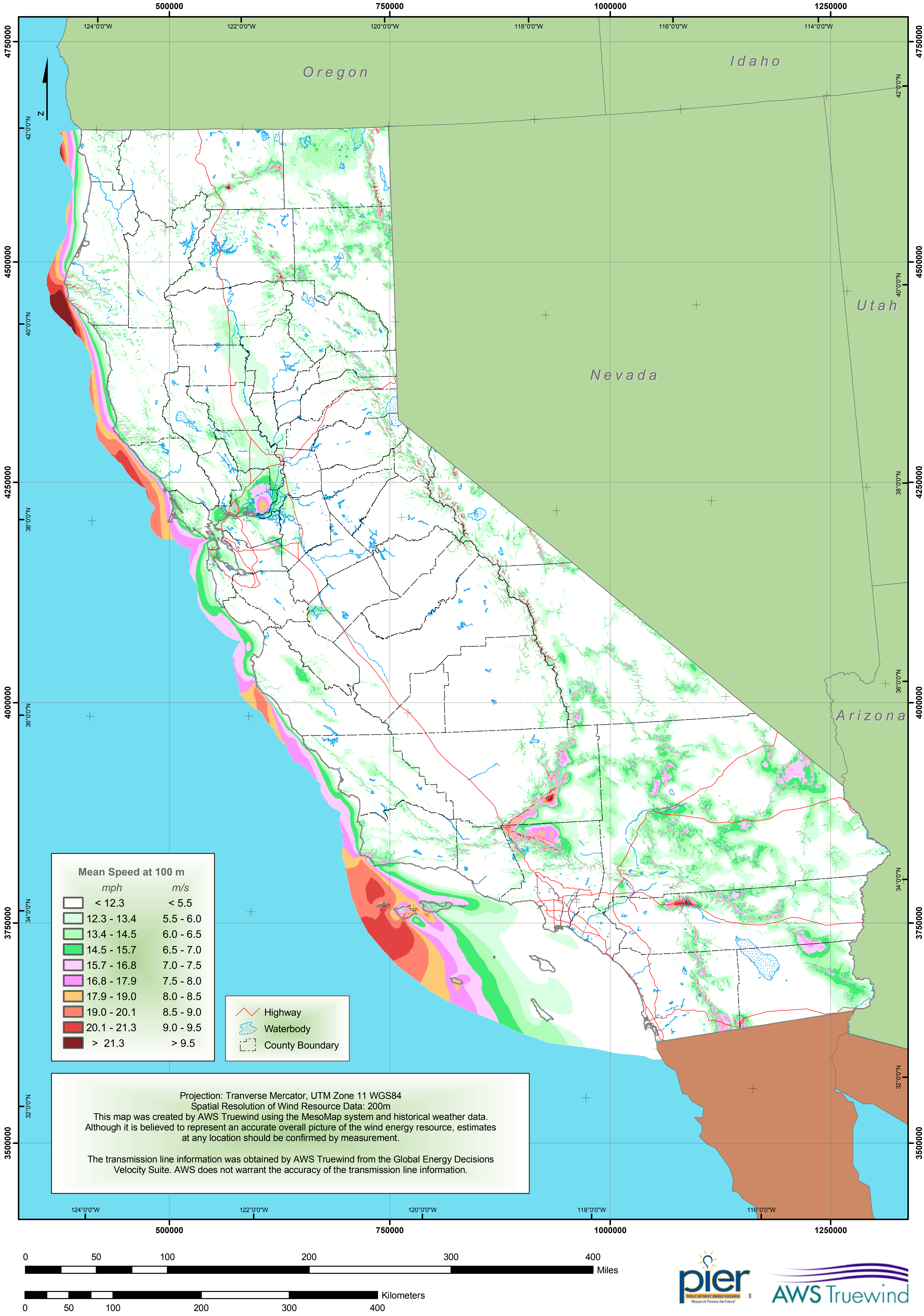
Mean Annual Wind Speed of California at 100 Meters



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